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Original Paper

Study on the Alternating Flow Hydraulics and Its New Potential Application in the Geotechnical Testing Field

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Abstract

The alternating flow hydraulics (AFH) had demonstrated the unique features in the past. One of the most well-known inventions was the hydraulic machine-gun synchronizer, which had become the standard equipment of airplane during World War I. The studies on the AFH between 1960 and 1980 had trigged many researchers' interests and reached the summit. The disadvantages of the AFH like low efficiency and cooling difficulty had prevented the further development. Few people are engaged in studying the AFH at present. However, the unique characteristics of the AFH inspire the researchers to continuously explore the new special suitable applications. The overviews of the AFH and the new potential application in the geotechnical testing field have been discussed in this paper. First, the research results of the AFH in the past have been summarized. Then, the classifications of the AFH have been introduced in detail according to the working principle, the number of hydraulic transmission pipelines and the mode of input energy. The advantages and the disadvantages of the AFH have been discussed. A novel potential suitable application in the soil test field has been presented at last. The detailed designing ideas of a new dynamic trixial instrument have been given, which will be a more innovational and energy-saving plan according to the current studies. A series of simulation experiments have been done. The simulation results show that the proposed scheme for the new dynamic trixial instrument is feasible. The paper work will also give some inspirations in the reciprocating motion control system.

Keywords: alternating flow hydraulics, hydraulic transmission, dynamic trixial instrument

1. Introduction

Alternating flow hydraulics (AFH) refers to a kind of hydraulic power transmission system in which power is transmitted through the actions and interactions of periodically-varying pressures and flow rates, with no net flow of fluid in the power transmission line. The ideas on the use of energy waves to transmit power formed the basis for the George Constantinesco's book-Theory of Wave Transmission, which was published in 1922 [1]. Dealing with the transmission of power by periodic forces and motions through liquids, solids and gases helped Constantinesco to found the theory of Sonics. The first hydraulic motor driven by the energy waves that produced by the generation of impulses by a hydraulic pump in a closed circuit was invented by Constantinesco in 1913. Then, prototypes of rock drills working on the percussion system and polyphase rotary systems were built, which were capable of boring through hard granite rock, quietly and smoothly compared to a pneumatic drill. One of the most famous inventions was a hydraulic machine-gun synchronizer (or interrupter gear, or "CC" gear), which allowed airplane-mounted guns to shoot between the spinning blades of the propeller. This Constantinesco synchronization gear was first used operationally on the D.H.4s of No. 55 squadron R.F.C. from March 1917, during World War I, and rapidly became the standard equipment. Based on the theory of wave transmission, Constantinesco built a prototype four phase system for the marine use with the generator running at a high speed and the propeller running at a low speed [2].

Following Constantinesco, the transverse velocity gradient near the mouths of pipes in which an alternating or continuous flow of air was established by E G Richardson and E Tyler in 1929 [3]. Arthur S. Iberall developed the elementary theory of transmission lags and discussed the corrections in instrument lines in 1950 [4]. Shigeo Uchida studied forced oscillatory incompressible flow in pipes in 1956 [5]. F. T. Brown analyzed the steady-state forced oscillations with transient effects in fluid filled pipes in 1962 [6]. K. Foster and G. A. Parker studied transmission of power by sinusoidal wave motion through hydraulic oil in a uniform pipe in 1964 [7]. The viscous power losses in a liquid-filled pipe under oscillatory compressible flow conditions had been analyzed. An 80 ft long pipe with diameter 7/8 and Shell Tellus 27 oil was used in the test. The results showed that the

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efficiency would be decreased and the power capacity depended upon the frequency of operation of the pipeline when the load was not equal to the characteristic impedance of the pipe. Then, F. Pollard summarized the scholars' researching results and discussed the basic designing concepts & components that were peculiar to AFH system in 1965 [8]. Cheng-kuo Weng had done theoretical and experimental investigations on fluid-power transmission in hydraulic systems by pulsating flow in 1966 [9]. The system efficiency and the viscosity effect on the dynamic response of pulsating flow in the fluid line had been studied. The line-loss test setup and the miniaturized P-F hydraulic system setup had been built. Eizo Urata and Toshio Takenaka etc studied the AFH system and calculated the characteristics of the AFH with single conduit, containing a separator and the three-phase AFH in 1974 [10]. G. L Fox, JR studied pressure wave transmission in a plastically deforming pipe in 1974 [11]. The results of the analysis showed that at fluid pressures less than the pipe yield pressure, waves were transmitted at elastic wave velocity. However, at pressures which exceed the pipe yield point, wave velocities were substantially reduced and the waves were dispersed. P. R. Ukrainetz and EI Ibiary. Y introduced a three phase pulsating flow hydraulic control system in 1978 [12][13]. D. Davis and P. Dransfield discussed broadly some theoretical considerations on the design of the AFH system and had discussed the methods of obtaining efficient transmission of power to a driven load and for regulating power in 1983 [14]. Walid Ahmed Mohammad studied the effects of pulsating flow (the high frequency pulsation effects and the compressibility effects) on differential pressure flowmeters in 1982 [15].

At the beginning of the 21st century, the AFH once again got many scholars' attentions. Hadj-Taïeb and E. Lili studied the pressure variations of the water hammer in deformable pipes in 2000 [16]. Carpenter, P studied the pressure wave propagation in fluid-filled co-axial elastic tubes in 2003 [17][18]. Mika Ijas clarified what kind of damper was bet for rock drilling machines through studying the operation of pressure damper sensitive to form of pressure wave (sine wave or irregular wave) in 2007 [19]. Zhongguo Sun investigated fundamental phenomena of pressure wave transmission in an energy absorbing liquid with MPS method in 2009 [20]. The results showed that larger viscosity and density of liquid would damp the energy of pressure wave faster. The effect of viscosity on wave speed and wave length was not evident. Ioan I. Pop and Ioana Denes-Pop tried to use a two-phase AFH system to realize a sonic transmission in 2009 [21]. They pointed out that the application of this system brought the bulk of equipments on the ground, making easier the problem of mounting, maintenance and repairing, less dangerous for human operators and less costly. Ding Wen-si and Wu Hui-yan analyzed the AFH system and the results showed that the vibration characteristic and transmission efficiency of the pulsating flow hydraulic system were decided by load characteristic besides pipe characteristic in 2010 [22]. Ioan-Lucian MARCU and Daniel-Vasile Banyai presented a prototype of rotary hydraulic motor, which could work using alternating flows in 2011 and 2012 [23][24]. They gave us some considerations regarding the basic calculation formulas, the design and testing principles for a hydraulic motor driven by alternating flow, and also a three-phase rotary hydraulic motor. Some other special applications studied on the pressure waves of blood pulse and the water hammer. The form of the pressure wave of blood pulse was considered to be closely related with the condition of aortic in medical field in 1980 [25], 1992 [26] and 2009 [27]. It was reported that typical shape of the wave may corresponded to the certain disease of aortic.

In summary, many followers after Constantinesco have done a lot of original work on the AFH. The AFH will be more widely recognized in the future. Our research group was founded to find some new applications of the AFH in the special suitable fields. The group hopes that the transmission of the AFH will be more popular as alternating-current energy transmission that took place in the electrics. In this paper, the classifications of the AFH have been presented. Advantages and disadvantages of the AFH have been discussed. The novel potential suitable application in the soil test field has been presented at last. The detailed design ideas of a novel dynamic trixial instrument have been given, which will be a more potential, innovational and energy-saving plan according to the current studies. This study will give some inspirations to other engineers in designing the similar applications.

2. The Classifications and Features of The AFH

The AFH could be classified into different forms in the past according to the working principle, the number of hydraulic transmission pipelines and the mode of input energy. Today these classifications are still recognized by the present researchers. In this paragraph, the classifications are summarized to clearly describe the AFH.

2.1 The Working Principle

According to the working principles, the AFH can be classified as pulsating hydraulic system and standing wave hydraulic system as Fig.1 and Fig.2 show [28]. In Fig.1, the pipeline is fix-mounted. The fluid in the pipeline moves back and forth with a certain amplitude and frequency relative to its mean position. The hydraulic pressure is determined by the load. Its changing has relation with the time t. The standing wave will be produced in Fig.2, which can be used to transmit the information. Nodes and antinodes are formed. As we all know the pressure of node will be always zero and the pressure of antinode will be alternately changing from the minimum to maximum. No special application but signal transmission for standing wave hydraulic system has been found until now.

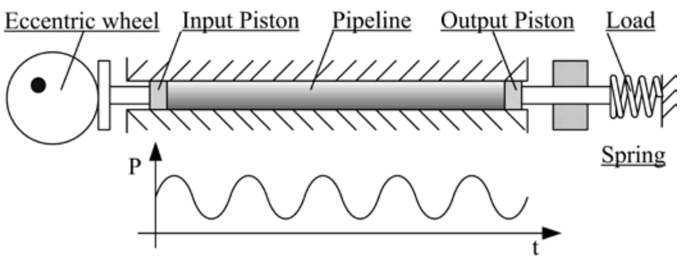

Fig.1 Pulsating hydraulic system (One-phase AFH system)

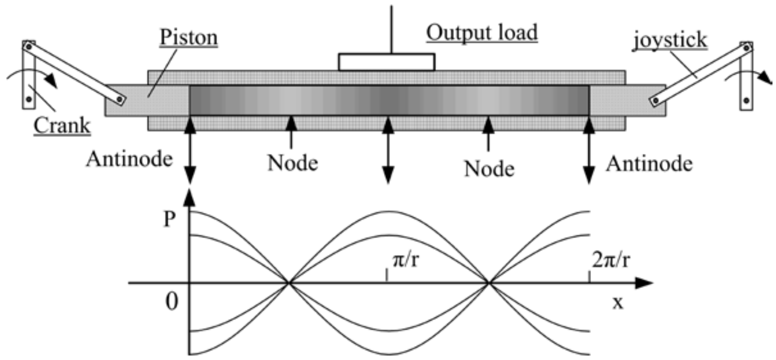

Fig.2 Standing wave hydraulic system

2.2 The Number of Hydraulic Transmission Pipelines

According to the number of hydraulic transmission pipelines, the AFH can be classified as one-phase AFH system, two-phase AFH system, three-phase AFH system, etc. One-phase AFH system is the same as the Fig.1. Two-phase AFH system and three-phase AFH system are shown in the Fig.3 and Fig.4 [29]. As above discussed, the AFH systems are widely used in the vibration conditions like rock drill, jig, hydraulic exciter, road surface fatigue testing machine, combine harvesters, hydraulic riveting machine and other machines for chipping, crushing, piercing and presses requiring rapid action. Base on the three-phase AFH system, Ioan-Lucian MARCU and Daniel-Vasile Banyai had designed a prototype of special rotary hydraulic motor (a three-phase rotary hydraulic motor) in recent years [11][12].

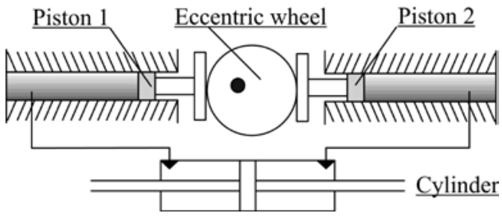

Fig.3 Two-phase AFH system

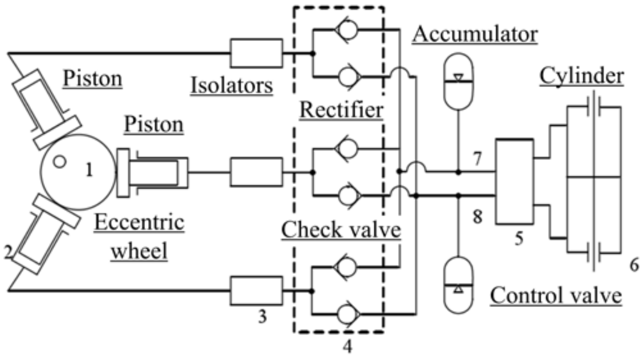

Fig.4 Three-phase AFH system

2.3 The Mode of Input Energy

According to the mode of input energy, the AFH can be classified as the constant flow source system and the constant pressure source system [28]. The systems in Fig.1, Fig.3 and Fig.4 are all belong to the constant flow source systems. The common things that this kind of system has are constant flow and fewer components. The constant pressure source system is different, which usually has the hydraulic power system like pump and relief valve to supply the sufficient constant-pressure fluid. There will have more components compared with the constant flow source system. In this kind of system, frequency control valves are used to realize the alternating movement.

2.4 Advantages and Disadvantages

The advantages of the AFH are clear. Besides the common advantages that the hydraulic transmission system possessing such as it's smooth, reliable and powerful, the AFH has its own unique advantages. The AFH system could withstand a wide range of temperature change or strong radioactivity by using isolator [8][12]. For example, liquid metal can be used to isolate parts from being destroyed in the super high temperature condition. The ability to isolate a fluid that would be subjected to the extreme environmental conditions or highly radioactive environments made the AFH system more attractive. The pressure can be changed easily by using different cross-area pistons. The AFH system is easy to accomplish the accurate flow distribution, which could meet some special requirements in speed or movement synchronization control. The AFH system is very important because of less cost and smaller components.

The disadvantages of the AFH also can be easily seen. The efficiency of the AFH is not very high enough, which is determined by the frequency of the joystick, the diameter & the length of the transmission pipeline and the working pressure. The relative low efficiency is probably the common disadvantage of the hydraulic system [9][28]. It is worth to mention that the alternating flow will shorten the lifetime of the components. The long-life high-strength components and special seals will be needed. Since there is no net flow in transmission, the last disadvantage is that the AFH system is difficult to cool because of non-circulating fluid.

3. New Potential Application

Many scholars have done a lot of work on the AFH and they do have useful results. However, study on the AFH exciting technology is very scarce. The reason is that the AFH exciting technology has some technical difficulties such as the traditional complex adjusting-frequency device and distorting pressure waveform. The pressure waveform is easily affected by the load in the AFH exciting system, so it is very difficult to get the perfect waveform. The accuracy of the flow waveform in the AFH exciting system is very high relative to the pressure waveform, which could be used in the displacement synchronization control system similar to hydraulic machine-gun synchronizer. Notably, the flow amplitude of the AFH exciting system will not decrease when the frequency increases. The AFH exciting technology has a great advantage in this aspect and its unique character is unmatched by other exciting systems. Few new applications have been found or reported recently and most of works focus on the theory study. This paper plans to use the high-precision flow waveform combining servo motor drive technology and advanced control strategies to get high-precision pressure waveform. The AFH exciting system with its unique character is very cheap and reliable, which will be one of best choices for the high-precision reciprocating force control system in the future. The dynamic trixial instrument is a high-precision force control device with harsh demands for the pressure waveform (sine wave) in the soil test field. The application of the AFH system in the dynamic trixial instrument will be a more potential, innovational and energy-saving plan.

3.1 Background of the Dynamic Trixial Instrument in the Soil Test Field

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 at different initial stress conditions and periodic loads is the basic needs for 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 dynamic triaxial instrument is used to simulate periodic excitations (sine wave, triangle wave, rectangular wave, etc.), which is a very important device for studying the instability, the stress/strain and the other mechanical properties of the soil.

An initial dynamic triaxial instrument was first developed in 1970s [31]. More and more world famous companies such as: GDS Company (British), GEOCOMP Company (USA), SHIMADZU Company (Japan), MELYTEC Company (Russia) etc. are engaged in developing similar instruments at present. In addition, some institutions had developed the dynamic trixial instruments by themselves like Wuhan University of Technology [32] and Dalian University of Technology [33][34]. Most present dynamic trixial instruments are built by the electro-hydraulic servo systems, the pneumatic servo system and the servo motor system. The electro-hydraulic servo system with its good dynamic response is widely recognized. The disadvantages of the electro-hydraulic servo system also cannot be omitted. The manufacturing cost and the operating cost are relatively high. This urges us to think if there is another way to build the dynamic trixial instrument or not. The AFH system will be one of the best ways to build the dynamic trixial instrument with low cost based on the present study.

3.2 Experiments of the Dynamic Trixial Instrument

There are different sizes of the dynamic trixial instrument from the normal size to middle size and huge size. The appropriate sizes of the soil cylindrical specimens are not the same such as: 39mm (diameter)*80mm (length), 61.8mm*100mm, 61.8mm*150mm, 450mm*300mm, 300mm*600 mm etc. The most commonly used size is 61.8mm*100mm. In this condition, the cross-sectional area of the cylindrical specimen is about 3000 mm^2. The test is over when the deformation ratio in length direction reaches 10%-20% of length, which is the judging criterion for the test. Dynamic modulus test and dynamic liquefaction test are two kind of necessary tests. Dynamic modulus is the ratio of stress and strain under vibratory conditions (calculated from data obtained from either free or forced vibration tests, shearing test, compression, or elongation), which will be calculated by measuring the velocity of the sonic pulses in the soil specimen. Soil liquefaction describes a phenomenon whereby a saturated or partially saturated soil substantially loses strength and stiffness in response to an applied stress, usually earthquake shaking or other sudden change in stress condition, causing it to behave like a liquid. Dynamic liquefaction test is performed to determine the soil's resistance to liquefaction by observing the number of cycles of loading at particular shear stress amplitude before its failure. In the dynamic modulus test, the confining stress will be divided into 3-6 grades from 50kPa to 300kPa and the range of the corresponding displacement will be changed from ±0.25mm to ±4mm by using 1Hz, 10 cycles sinusoidal stress. In the dynamic liquefaction test, the confining stress is defined by the axial sinusoidal stress, which is 1Hz, 50-100 cycles and 50-200kPa stress.

The plan in this paper is based on the most common used cylindrical specimen (61.8mm*100mm). A lot of tests have been done in the past. According to testing data, typical dynamic modulus test result and typical dynamic liquefaction test results are shown in Fig.5, Fig.6 and Fig.7. From the Fig.5, it can be seen that the stepped stress changes are about from ±5Kpa to ±100/±150Kpa. The loading stress in each step is standard sine wave. There will be an interval about 3-5 minutes between two steps. The total dynamic loading will last 150-300s. However, the whole dynamic experiments will last 50-100 minutes if the interval between two steps is considered. In addition, it is worth mentioning that the saturation experiment (the static loading test) needs to be done before the dynamic loading test. The process of the static loading will last 5-24 hours.

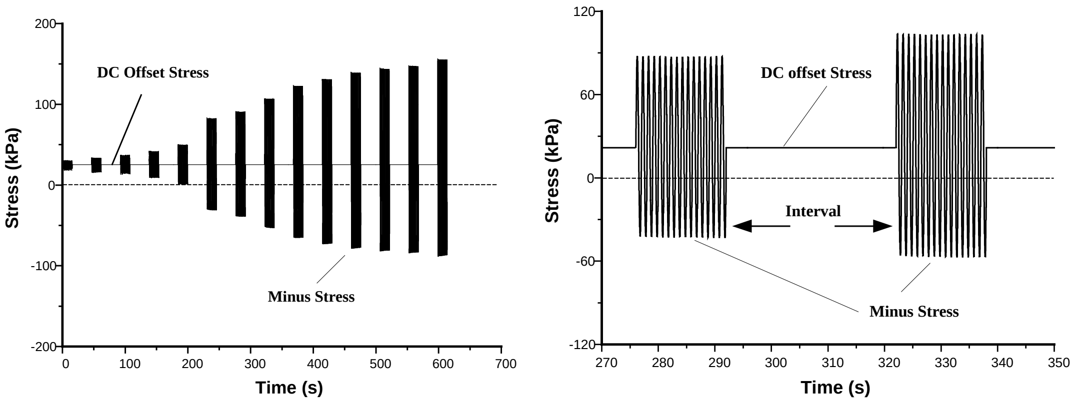

Fig.5 Typical dynamic modulus test results

The figures on the left in Fig.6 and Fig.7 show the dynamic stress. The dynamic stress is standard sine wave, which is 1Hz, 50-150 cycles. The figures on the right in Fig.6 and Fig.7 show the corresponding displacement. They look like the bell shapes. The displacement changes will become bigger and bigger. But the maximum change is less than ±4mm. The dynamic liquefaction test also needs the saturation experiment (the static loading test) and the process of the static loading will also last 5-24 hours. The apparent difference between the dynamic liquefaction test and the dynamic modulus test is that the liquefaction is done in one time and it lasts about 50-150s.

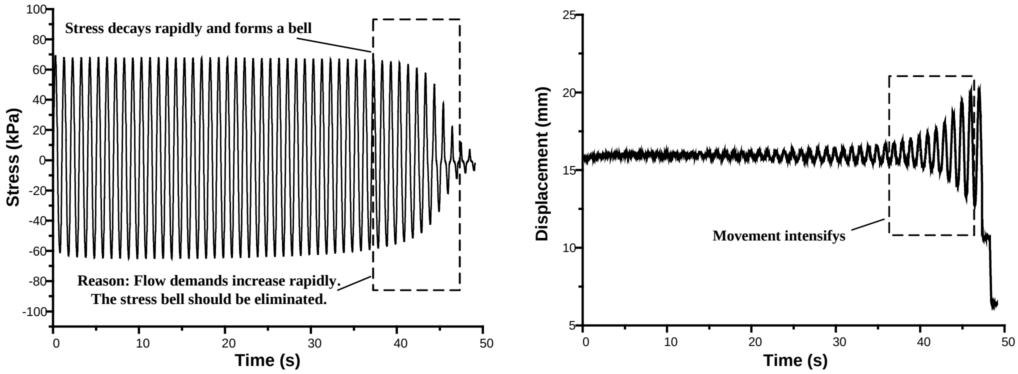

Fig.6 Typical dynamic liquefaction test results (1)

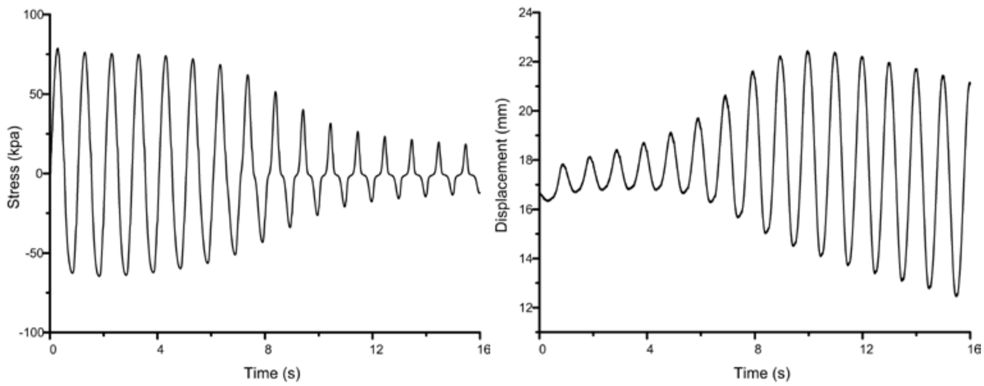

Fig.7 Typical dynamic liquefaction test results (2)

3.3 The Schematic Diagram of the New Dynamic Trixial Instrument

Based on the above testing data and the AFH exciting technology, a new dynamic triaxial instrument has been planed as Fig.8 shows. The new dynamic triaxial instrument contains the driving subsystem, static balancing control subsystem, elastic modulus adjusting subsystem and application subsystem. The driving subsystem is composed of servo motor 1, flywheel, gearbox, crank structure, leverage structure, servo motor 2 etc. Servo motor 1 provides the power and the constant speed. Flywheel is used to guarantee a constant speed. Gearbox is used to realize the torque transform. Crank structure is used to change the rotary motion into the linear motion (sine wave). Leverage structure is used to realize the torque transform and the displacement transform. Servo motor 2 is used to adjust the displacement of the leverage fulcrum. The static balancing control subsystem is composed of cylinder, screw/nut and servo motor 4. Servo motor 4 is used to drive the screw-nut system to generate the required static water pressure, which is also used to compensate the system leakage and other volume changes such as displacement change of soil sample and mechanical volume change in balance. The elastic modulus adjusting subsystem is composed of cylinder, springs, servo motor 3 and bidirectional screw. The springs are used to linearly change the sine flow into the sine pressure. The bidirectional screw can generate the opposite or reverse movement, which is used to adjust the total elastic modulus of the springs (k_1 , k_2) by changing the angle between spring k_1 and spring k_2 . The application subsystem is composed of cylinder, force/displacement sensor and pressure vessel. The cylinder is used to generate the definite pressure/stress and the force sensor is used to measure it. The amplitude of the pressure/stress applying on the specimen is adjusted by the elastic modulus adjusting subsystem and the flow is adjusted by the leverage structure.

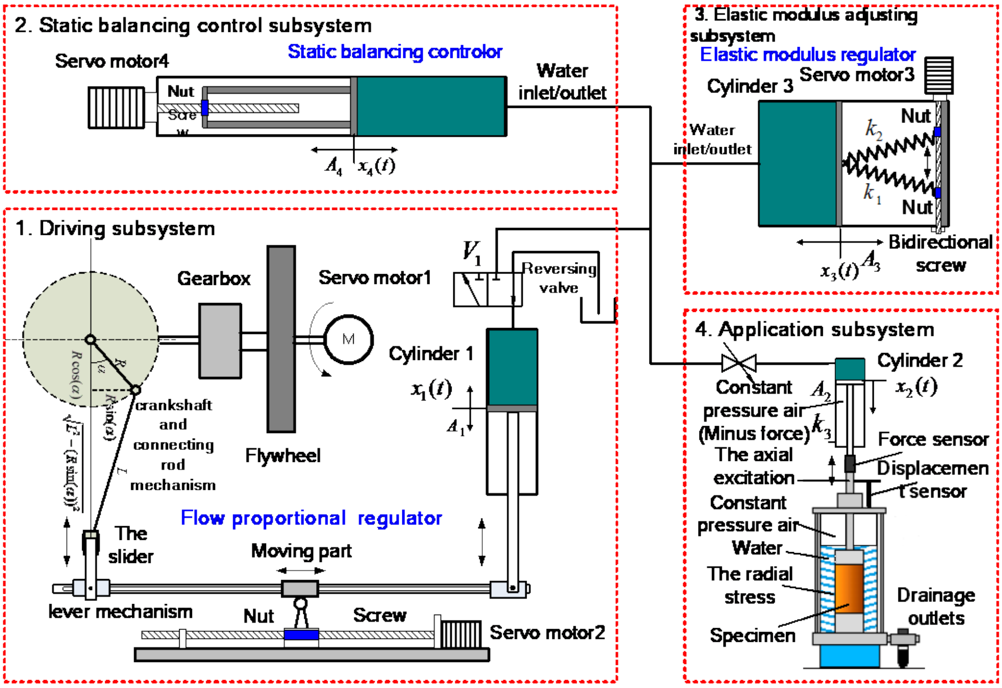

Fig.8 Schematic diagram of the new dynamic triaxial instrument

3.4 The Advantages and the Disadvantages of the New Dynamic Trixial Instrument

The unique advantages of the new dynamic trixial instrument are clear. First, it's an energy-saving plan. For typical dynamic liquefaction test and typical dynamic modulus test the process of the static loading will last 5-24 hours, but the total dynamic loading only last 150-300s. The new dynamic trixial instrument based on the AFH will be an energy-saving plan because the driving subsystem (the servo motor1 and servo motor2) will not work during the static loading process; Second, the plan could solve the "bell-shape" problem. According to the results of measuring the displacement and system requirements, the flow can be easily adjusted by the leverage structure. So there will be no more "bell-shape" problem; At last, Due to the relative lower bandwidth of the hydraulic system, the frequency of the pressure/stress is less than 20-30Hz. However the frequency of the pressure/stress based on the AFH can easily reach 200Hz (Servo motor: 3000r/min and gearbox/ratio: 4/1) or even bigger like 500Hz (Servo motor: 3000r/min and gearbox/ratio: 10/1) in theory.

There are also disadvantages that need to be considered as followings: (1) It is not easy to obtain the high-precision frequency of the AFH. The frequency is determined by the speed of the servo motor 1. However, the DC offset pressure/stress and outside loading will bring the interference to the speed of the servo motor 1. The control accuracy of frequency will be reduced. Therefore, the ways that improving the speed robustness of the servo motor 1 should be considered to ensure the control accuracy of frequency. (2) It is hard to realize multi-motors synchronous control to regulate the flow/pressure of the AFH. According to the movement of the load (measuring by the displacement sensor) the flow/pressure of the AFH should be adjusted in real time. Therefore, a feasible way to realize the synchronous control of servo motor 2, servo motor 3 and servo motor 4 should be found.

3.5 The Solutions for the Disadvantages

The frequency of the AFH depends on the servo motor 1. The servo motor 1 requires precise speed control and high robust. The optical encoder is supposed to use to measure speed and the inverter servo motor is used to realize the close-loop control. In order to obtain the high-precision frequency, the speed robust will be improved from the hardware aspect and software aspect in this plan (Fig.8 shows). In the hardware aspect, a mass flywheel will be mounted between the servo motor 1 and gearbox. It is used to store energy to improve the speed robust. In the software aspect, a fuzzy-PID robust control algorithm will be applied in the speed control. Therefore, the speed robust will be improved significantly.

The multi-motors synchronous control is not a new concept. The cross-coupling control and master-slave control are used to realize the synchronization control in this plan. The hydraulic oil is recommended to avoid the non-linear friction influence. The most famous research (cross-coupled control) on the high precision synchronous control was proposed by the Professor Y.Koren (University of Michigan, USA). The core idea was that synchronized control was realized by the coupling effect and the relative motion. This synchronized control could effectively improve the interactive synchronization between the controlled the subsystems and greatly improve the tracking accuracy. Therefore, the high-precision synchronous control could be realized.

4. Simulation Study of the New Dynamic Triaxial Instrument

To verify the practicability of the proposed scheme, the paper accomplishes a series of simulation experiments. The new dynamic triaxial instrument contains the driving subsystem, the static balancing control subsystem, the elastic modulus adjusting subsystem and the application subsystem, among which the driving subsystem and the elastic modulus adjusting subsystem can lead to distortion of flow wave and pressure wave. The driving subsystem, the elastic modulus adjusting subsystem, the application subsystem are principle effects which produce distortion of pressure wave, other nonlinear links such as friction, compressibility of liquid and so forth have relatively less influence on distortion of wave. According to knowledge of fluid dynamics, other systematic nonlinear effects are ignored to simplify the model of simulation. The following assumptions have been made in the paper: 1. Rotation speed of servo motor is constant; 2. Single spring is linear; 3. The mechanical friction in the system is neglected; 4. The liquid is ideal and there is no compressibility and mass in the liquid; 5.The mechanical structure is rigid; 6. There is no leakages of the system; 7. Location control error of servo motor is ignored; 8. The temperature of working is constant.

4.1 The Motion Equations for the Key Subsystems

In the driving subsystem, the sine flow wave is generated by the crankshaft and connecting rod mechanism. Under the assumption of constant speed of servo motor, crankshaft and connecting rod mechanism itself may result in the distortion of flow wave, thus it is very necessary to analysis the degree in which crankshaft and connecting rod mechanism contributes to distortion error of flow wave. As for the elastic modulus adjusting subsystem, it is used to proportionally transform the variance of quantitative volume to variance of pressure. The changes of piston motion will bring about tiny changes of elastic modulus in the process of transformation. Therefore, it is necessary to analysis the degree in which tiny change of elastic modulus influences the distortion error of pressure wave. In addition, the static balancing control subsystem may just control static pressure, which leads to no distortion of dynamic wave. According to the property of triangle of similar triangle, the displacement (velocity) transformation of two ends of lever is linear and causes no distortion of pressure wave. The application subsystem is designed to accomplish dynamic loading work, which can be assumed as a disturbing factor in the simulation analysis. In brief, the driving subsystem, the elastic modulus adjusting subsystem and the application subsystem are mainly considered to analysis the influence of pressure wave in this paper. The following lists the motion equations in the driving subsystem and the elastic modulus adjusting subsystem:

$$x = R\cos\alpha + \sqrt{L^2 - (R\sin\alpha)^2} \tag{1}$$

$$\alpha = \omega t \tag{2}$$

$$\omega = \frac{2\pi n}{60} \tag{3}$$

$$x_3 = \frac{r_1}{r_2}x \tag{4}$$

$$PA_3 = 2k\frac{(l-x_3)x_3}{\sqrt{(l-x_3)^2 + (\frac{d}{2})^2}} \tag{5}$$

$$tg\frac{\partial}{2} = \frac{d}{2l} \tag{6}$$

4.2 The Wave Distortion Analysis for the Driving Subsystem

In the driving subsystem, crankshaft and connecting rod mechanism is not a standard sine wave. There exists a wave distortion error between standard sine wave and motion of slider. The magnitude of distortion error depends on crank length R and the length of the connecting rod L. Theoretically, the smaller ratio of length of crank R to the length of the connecting rod L is, the better the linear system is. In order to study the relationship among R, L and distortion error, dimensionless L/R is selected as a variable, and the error analysis is accomplished through MATLAB. The simulations are done on the condition of L/R = 2, 4, 6, …, 30 when n =60 rev/min (1 Hz). Figure 9 shows the relationship between L/R and wave distortion error.

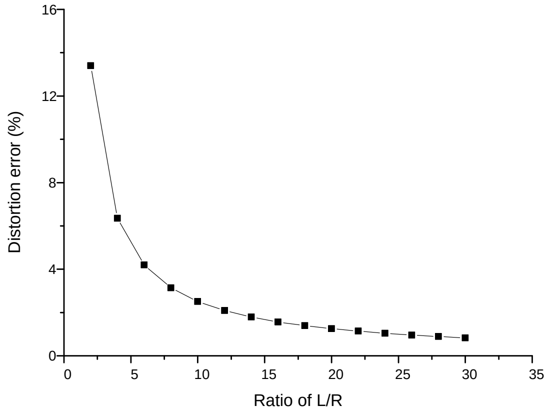

Fig.9 Diagram of relationship between L/R and wave distortion error

According to Figure 9, when L/R=2, the distortion error reaches approximately 13.5%. As the value of L/R increases, the distortion error decrease sharply until the ration is about 5. When L/R=6, distortion error reaches approximately 4%. Distortion error will decrease slowly if the value of L/R is higher than 15. The distortion error decrease slowly if the value of L/R continues to increase. The relative error is less than 2% if the value of L/R is larger than 14 and the relative error is less than 1% if the value of L/R is larger than 28. Therefore, it can be concluded that if proper value of L/R is selected, the approximately ideal sine flow wave can be produced.

4.3 The Wave Distortion Analysis for the Elastic Modulus Adjusting Subsystem

The influence produced by the elastic modulus adjusting subsystem on pressure wave is analyzed. The piston in the elastic modulus adjusting subsystem moves up and down near the balance point when it is in working condition, The up and down motion will change the angle between two linear springs, which will lead to the variance of the total elastic modulus. The transformation from liquid volume to liquid pressure is not linear any more, which produces distortion of pressure wave and leads to pressure error. Fortunately, if the motion of piston near the balance point vary very little, and the angle between two linear springs has a tiny change, which results in very small error. There is the proper range of error that the transformation between liquid volume and liquid pressure can be seemed as linear. According to the schematic diagram of the elastic modulus regulator, it is not hard to recognize that the degree of linearity is worst when the angle reaches $\pi/3$ (the range of angle is $0-\pi/3$). If the distortion error of pressure meets the requirement in the extreme condition, the distortion error of the total elastic modulus caused by elastic modulus regulator in other conditions will be less. After dimensionless ratio of lever as a variable is selected, when extreme angle equals $\pi/3$, the error analysis are accomplished through MATLAB. The simulations are done on the condition of ratio of lever= 1, 1.5, 2, …, 5, when n=60 rev/min (1 Hz). Fig.10 shows relationship between ratio of lever and wave distortion error.

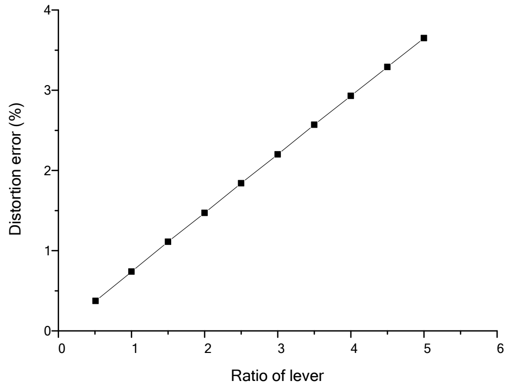

Fig.10 Diagram of relationship between ratio of lever and wave distortion error

According to Fig.10, when ratio of lever is equal to 1, the distortion error reaches approximately 0.8%. As ratio of lever increases, distortion error correspondingly increases similarly proportionally, when ratio of lever is equal to 5, the distortion error reaches approximately 3.65%. It can be concluded that if the proper ratio of lever is selected, the approximate ideal pressure sine wave can be produced.

4.4 The Integrated Wave Distortion Analysis

Combining the driving subsystem with the elastic modulus adjusting subsystem, the simulation shows the flow wave distortion caused by the driving subsystem and pressure wave distortion caused by elastic modulus adjusting subsystem will cancel each other, and total distortion error will decrease sharply, which is significant to the transformation from liquid to pressure for the crankshaft and connecting rod mechanism. In other words, the piston motion of elastic modulus adjusting subsystem and ratio of lever can change in a relative larger range. The integrated distortion error under certain conditions is shown in Fig.11.

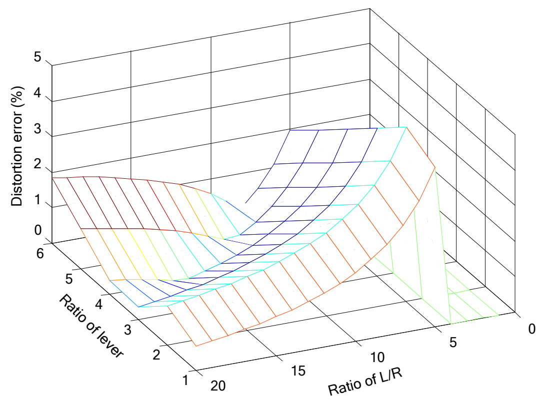

Fig.11 Diagram of the integrated wave distortion error

In Fig.11, x axis represents the ratio of L/R, y axis represents ratio of lever, z axis represents the total distortion error. From the Fig.11, it can be known that when L/R and ratio of lever are given the proper value, the nonlinear error of the system reaches the minimum value. The value of L/R is fixed for a determined lab system, however, ratio of lever can be adjusted randomly. If wave distortion error <2%, ratio of lever can be adjusted in a larger range. In turn, if the liquid flow varies in a larger range, the total distortion error of the system could be controlled within a permissible error range.

4.5 The Distortion Analysis of the Application Subsystem

The application subsystem is considered in the simulation analysis. The application subsystem can be seemed as the disturbance of flow. For specimen in Fig.8 (61.8mm*100mm), the component is sandy soil. The specimen is under the effect of standard sine excitation load and the piston moves a similar sine wave following changes of the specimen's height. Therefore the influence on pressure wave distortion caused by specimen's height in the dynamic triaxial experiment is studied under different pressure excitation load in simulation. The system simulation parameters are set (shown in Table 1) according to practical dynamic triaxial experimental data. Figure 11 shows the influence on total pressure wave distortion caused by axial stress under the condition that axial stress is 50kPa and 100kPa.

Table 1 The simulation parameters in the application subsystem

R	30mm	Ratio of lever	0.1-6
L	840mm	Axial stress	50kPa/100kPa
n	60r/min	Maximum amplitude	$\leq$2.0mm/4.0mm
k	78.5N/mm	Piston diameter of Cy.3	64mm
D	200mm	Angle between springs	0

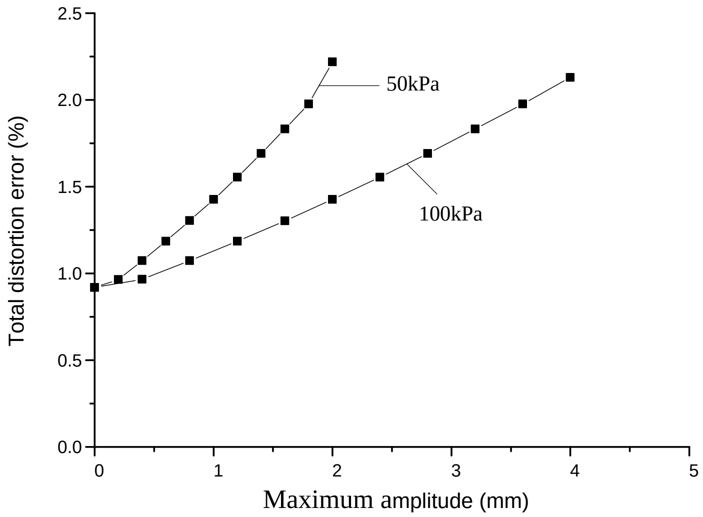

Fig.12 Diagram of total distortion error of the proposed scheme

Total distortion error of the proposed scheme is shown in Fig.12. From Fig.12, under the conditions of different axial stress, the maximum deformation has the most influence on the total pressure wave distortion. When axial stress is 50kPa, the maximum magnitude of the specimen deformation equals 2.0mm, the maximum total pressure wave distortion error is 2.2%. When axial stress is 100kPa, the maximum magnitude equals 4.0mm, the maximum total pressure wave distortion error is 2.13%. From the simulation results, pressure wave maximum distortion error could be controlled less than 2.5%. The maximum distortion error is relative small and it will meet the requirement of dynamic triaxial experiment. Thus, it can be concluded that the proposed scheme is feasible.

5. Conclusion

AFH has been studied in this paper, which has aroused some researcher's attention. Some researchers hope that the AFH can be used freely, easily and simply like AC voltage in our daily life. Based on such a point, people can understand the AFH more clearly through this paper work. The classifications of the AFH have been introduced in detail according to the working principle, the number of hydraulic transmission pipelines and the mode of input energy. The advantages and the disadvantages of the AFH have been discussed. A typical potential application has been presented, which is applied in the soil test field. The present study shows the dynamic trixial instrument design based on the AFH will be a more potential, innovational and energy-saving plan. In order to verify the practicability of the proposed scheme, a series of simulation experiments have been accomplished. The simulation results show that the proposed scheme for the new dynamic trixial instrument is feasible. In addition, our research group will continue to do research on the experiment and hope this paper would help the similar researchers to understand the AFH and its applications.

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Nomenclature

n	Rotation speed of the motor [rev/min]
ω	Angular speed of the crank [rad/min]
x	Displacement of the slider [mm]
L	Length of the connecting rod [mm]
R	Length of the crank [mm]
α	Angle of the crank [rad]
d	Length between two nuts [mm]
∂	Angle between two springs [rad]
k	Modulus of elasticity [N/mm]
r_1	Ratio of the lever
r_2	Ratio of the cross area of cylinder 1 and cylinder 3
l	Length between the piston and the baseplate in the cylinder [mm]
x_3	Displacement of the piston in the cylinder 3 [mm]
P	Pressure in the liquid [Pa]

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