PART 5: PRINCIPLES OF TESTING MACHINE CONTROL FEEDBACK

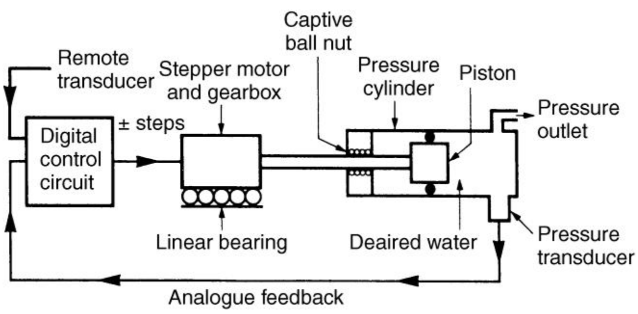
Prepared by the GDS Instruments Technical Team

Overview: The following 5 part series has been written to define the aims and means of the GDS computer controlled instrumentation and machines used in the testing of soil and rock for geotechnical and geological engineering purposes. The series comprises of the below topics. The series will be useful to those involved in design, engineering, commissioning, installation and training of GDS systems.

1. Key Terminology and Engineering Parameters for Geotechnical Engineering,
2. Principles of Instrumentation Measurement – Error, Accuracy and Resolution,
3. Calibration of Geotechnical Instruments
4. Selecting Ideal Transducer Range,
5. **Principles of Testing Machine Control Feedback.**

The control of machines in the soil mechanics laboratory can vary from the simple "on-off" variety that are operated manually to the more modern machines that are controlled by computer. The control can be "open loop" whereby the computer takes in measurements from a logger connected to transducers, carries out computations, and makes some decision such as to start or stop a test. The control can more likely be "closed loop", however, whereby the machine is controlled from a transducer on the test specimen (e.g. a radial strain transducer controlling a K_0 test), or from a transducer such as a load cell in a force actuator or loading frame. The transducer is providing "feedback" i.e. a direct measurement that can be compared to some set or target value. The microprocessor in the machine can then make the machine operate in such a way as to minimise the gap between the measured and target value so that the target value (which may be moving) can be achieved. This enables a digital solution to utilising feedback that, in the pre-digital age, made use of (analogue) process controllers to, for example, control K_0 consolidation and K_0 swelling in the triaxial apparatus (Menzies et al., 1977). Consider the following example of microprocessor control using feedback.

12 (a)



12(b)

Fig.12 (a) Photograph of the GDS Enterprise Level Digital Pressure Controller, ELDPC; (b) schematic diagram showing the principle of operation of the GDS digital pressure controller. Note the closed loop feedback (from Menzies, 1988).

Example: the GDS digital pressure controller

The GDS digital pressure controller shown in the photograph in Fig.12(a) is a microprocessor controlled hydraulic actuator or screw pump (Menzies, 1988). The principles of operation are shown in Fig.12(b).

De-aerated water in a cylinder is pressurised and displaced by a piston moving in a cylinder. The piston is actuated by a ball screw turning in a captive ball nut. The ball screw is turned by a stepping motor and gear box the move rectilinearly on a ball slide linear guide. Pressure is detected by means of an on-board pressure transducer. Control algorithms are programmed into the programmable memory chip ("firmware") to cause the controller to seek to a target pressure or step to a target volume change. Volume change is measured by counting the steps to the stepping motor.

Knowing the number of steps per revolution of the stepping motor, the gearbox ratio, and the pitch of the ball screw, the bore of the pressure cylinder may be calculated such that one step of the stepping motor equals $1mm^3$. Half-stepping and micro-stepping enable higher resolutions of volume change. The accuracy of volume change measurement is partly governed by the accuracy with which the bore can be machined. This is checked to be within set limits using a "go-no-go" plug gauge.

In stand-alone mode, the controller is a general purpose pressure source and volume change gauge. Through the controller's control panel, a target pressure may be set and the stepping motor will step to generate the set pressure. It does this by comparing the feedback from the on-board pressure transducer with the target pressure. If the difference is great, the motor will step at maximum speed. As the difference becomes less the motor executes fewer steps between A/D cycles and so it slows down until the gap is so small that it is within a tolerance of pressure equivalent to that generated by half a step or the resolution of the device (0.5kPa on a 2MPa device for 12 bit A/D). Then the controller is deemed to have reached its target under feedback control. In this way pressure can be generated and volume change measured, or volume change generated and pressure measured.

Means of control: pneumatic, hydraulic and electro-mechanical

Different manufacturers of dynamic triaxial systems use different means of control. These are: pneumatic, hydraulic and electromechanical. These control systems have different properties that affect the choice of system depending on the application. In particular, they have different performance characteristics in static and dynamic situations. It is therefore critical to the user's research programme that they make the correct choice of system and the corresponding means of control.

When we consider dynamic triaxial systems, the main area of discussion is related to the *dynamic performance of machines* – a subject that is widely taught in colleges and universities and well documented in text books and technical journals. Undoubtedly, hydraulic or pneumatic machines appear to out-perform (and are much cheaper than) electromechanical control at frequencies above 10Hz. The lack of precise control at these higher frequencies is the key consideration, however, and the user must decide the degree of inaccuracy they are prepared to accept. It is our experience that some suppliers of dynamic triaxial apparatus specify their equipment in terms of the performance of the system means of *input* e.g. the performance of a compressed air actuator or hydraulic valve. They do not specify the *output* i.e. what actually happens to the test specimen. *This gap between the supplier-specified input and the actual output at the test specimen level is an area of uncertainty that the user can only resolve by testing and then it is too late because the system has been purchased! It is better, therefore, to purchase equipment from a supplier who specifies their equipment in terms of output and not input*. Closed loop control whereby the test is controlled from a transducer on the test specimen (e.g. internal submersible load cell) is one obvious bench mark of good test systems. There are also some other general considerations that the user needs to understand in their evaluation of equipment before purchase. These now follow.

Servo Controlled Systems

Hydraulic control and pneumatic control are inherently pressure control. A flow control valve is used to vary pressure to control some associated parameter – position, pressure, force or torque. Controlling the pressure in the hydraulic actuator is straightforward. Real closed loop control of torque or force via torque and force transducers becomes more difficult due to non-linearity in the test specimen and friction in various seals. Accurate displacement control using hydraulic or pneumatic systems is much more difficult because:

- compressibility of the controlling medium (air or oil) combined with slip-stick in the actuation system causes nonlinearity in the control response, and
- digital closed loop control systems typically use 12 bit data acquisition in the control path and therefore resolution is only 1 in 2^{12} or about 4,000.

In contrast, an electromechanical solution typically uses brushless dc servomotors with digital control of position or speed using feedback from a remote transducer (load, torque or pressure). With regard to load, torque or pressure, electromechanical control is similar to that of a hydraulic system where a transducer is used in the primary control loop (load, torque or pressure) that is not perfectly related to the parameter being controlled by the motor (velocity or position) because of the combined non-linearity of the machine, soil and friction.

When it comes to position control, however, the motors are ideal because they have high resolution shaft encoders (8000 counts per revolution) and fixed gearing. This means that the axial displacement and rotation is known to a very high resolution of control that is better than a displacement transducer mounted externally to the test specimen being read by a 16 bit data acquisition system (i.e. with a resolution of 1 in 2^{16} or about 64,000). The control response to the feedback transducer output is therefore at very high precision giving good position control in both static and dynamic modes of operation.

Dynamic control

Hydraulic or pneumatic machines out perform in terms of speed (and are much cheaper than) electromechanical control at frequencies above 10Hz. The drawback is that there is a lack of precise control at these higher frequencies and users must accept the measurements are within about 5 percent of what is actually happening to the test specimen. In the 1-10Hz range, however, hydraulic and electromechanical control means are equally good (apart from accuracy of displacement and rotation control as described above). Below 1Hz the electromechanical systems are much better because they are able to maintain very accurate loads and positions over extended periods of time as well as having good dynamic performance.

In summary, above 10Hz choose hydraulic control, between 1 and 10Hz it is a matter of the user's preference. Below 1 Hz choose electromechanical control means. As the typical soil mechanics system will only spend less than 1 % of its operational life being used above 1Hz and 99% below 1 Hz (static soil testing is very slow!) the case for electromechanical control is also strong in the 1-10Hz range.

Stepping motor controlled systems (a static form of electromechanical control)

Stepping motor controlled systems are only suitable for static and very low frequency cyclic systems. They have the advantage of extremely stable short and long-term control of load, stress, displacement, pressure and volume change. They are also very economical when compared to servo controlled systems. This makes the stepping motor controlled devices ideal for the majority of typical non-dynamic geotechnical testing systems e.g. GDS pressure/volume controllers, load frames and force-displacement actuators.

Choice of systems

We advise using electromechanical control for the following applications:

- For static and dynamic soil/rock testing applications at frequencies less than 10Hz and loads less than 20kN (using brushless dc servo motors)
- For static and dynamic soil/rock testing applications at frequencies less than 2Hz and load less than 50kN (using brushless dc servo motors)
- For static loading applications for loads up to 250kN (using stepping motors).

We also recommend hydraulic control for the following applications:

Dynamic applications above 10Hz

- Testing requiring the application of large numbers of cycles, for example routinely applying more than 1000 cycles to test specimens - such as resilient modulus tests
- High load static applications above 250kN
- High load Dynamic applications above 2Hz and 50kN

Pneumatic control can be used in the following applications (but remember that the low cost comes with a different kind of price: low precision):

- Low cost stress control at very low forces (<5kN) e.g. using Bellofram actuators
- Applications requiring low precision repeated loading such as low load resilient modulus tests.
- Simple dynamic load control at low forces (<10kN)
- Low cost pressure control at pressures up to 1000kPa using either open loop manual control valves or closed loop computer controlled valves (like the GDS 2 channel air valve).

Triaxial Systems: Overview

The above considerations may be summarised as follows:

- *Below 1Hz use electromechanical control systems.*
- *In the range 1Hz-10Hz (i.e. earthquake range) use electromechanical or hydraulic (or pneumatic but with low precision) control systems.*
- *Above 10Hz use hydraulic (or pneumatic but with low precision) control systems.*
- *For both static and 1-10Hz dynamic (like the GDS 2Hz and 10Hz triaxial systems and 1Hz and 5Hz hollow cylinder apparatus') use electromechanical control systems.*

This is shown pictorially in Fig. 13.

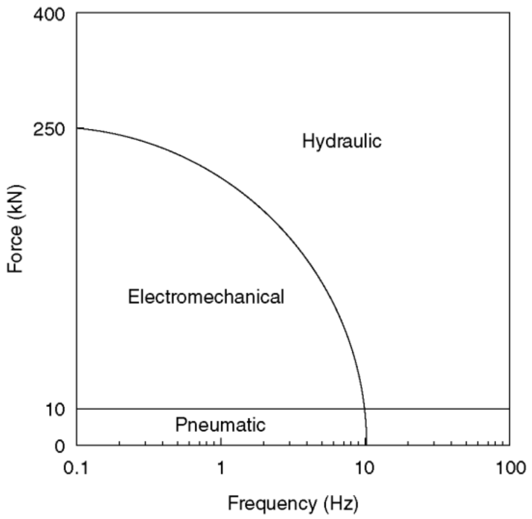


Fig. 13 Chart showing recommended regions of force-frequency relationships for optimum performance of dynamic triaxial testing systems actuated by pneumatic, hydraulic and electromechanical means.

Dynamic control systems

Dynamic control systems require an electronic high speed digital control system with closed loop feedback of displacement and load. For example, the GDS Dynamic Control System (DCS) uses 16 bit data acquisition (A/D) and 16 bit control output (D/A), and operates at a control frequency of 10kHz per channel. This means that when operating at 10Hz the system uses 1000 control points per cycle. When running at 1Hz, it uses 10,000 control points per cycle. GDS uses the same high speed control system throughout the range. Accordingly, the accuracy and resolution of the test control is only a function of the actuator used, whether it is a low-cost pneumatic actuator, high-accuracy electromechanical actuator or high-capacity hydraulic actuator. Given the inherent inertia and compliance of the testing machines, the actual performance that can be delivered to the test specimen, is of course different from the specification of the controlling system. As commented above, it is not sufficient for manufacturers to specify their equipment in terms of the performance of the system means of *input* e.g. the performance of a compressed air actuator or hydraulic valve, or as above, the dynamic control system. This can only be ascertained by calibrations involving geomaterial samples of the types to be tested with the intended system.

Reference:

Menzies, B. K., Sutton, H. and Davies, R. E. (1977). A new system for automatically simulating K_0 consolidation and K_0 swelling in the conventional triaxial cell. *Géotechnique* 27, No. 4, 593-596.

Menzies, B. K. (1988). A Computer Controlled Hydraulic Triaxial Testing System. *Advanced Triaxial Testing of Soil and Rock, ASTM STP 977*, Robert T. Donaghe, Ronald C. Chaney, and Marshall L. Silver, Eds., American Society for Testing and Materials, Philadelphia, 1988, pp. 82-94.