Abstract. Servo-hydraulic materials-testing machines operate under closed-loop control to apply
dynamic loads or extensions to test-specimens to simulate service conditions or to determine material
properties. Faithful demand following is not always possible with the current generation of fixed-
parameter PID controllers because specimen stiffness changes that occur during the test alter the
bandwidth of the control loop. Also, the controller has to be re-tuned every time a different specimen
is installed. An adaptive scheme is described which overcomes this problem by continually updating
the PID terms using real-time stiffness estimates. Adaptation is possible even when the test signals are
not persistently exciting.

Resumen. Las máquinas de ensayos de materiales servo hidráulicas operan bajo el control de bucle
cerrado para aplicar cargas dinámicas o extensiones a las probetas para simular condiciones reales o
para determinar las propiedades del material. El seguimiento real de la demanda no siempre es posible
con la generación actual de controladores PID de parámetros fijados, para que los cambios de rigidez
de la probeta que ocurran durante el ensayo alteren la banda de control. También, el controlador debe
ser sincronizado de nuevo cada vez que se instala una probeta nueva. Describimos el sistema adaptativo
para resolver el problema actualizando continuamente los términos PID usando estimación de rigidez
en tiempo real. La adaptación es posible incluso cuando las señales del ensayo no están
persistence mente excitación.

INTRODUCTION

This note describes Instron’s adaptive controller for
servo-hydraulic materials-testing machines. It provides
information requested by Keith Moon of Brewer &
Son to enable him to carry out a preliminary
assessment of the viability of some form of patent
protection for this invention. It outlines why adaptive
control is needed, what others have already done in
this field, the advantages of the Instron adaptive
controller and how it works.

The need for adaptive control

Adaptive control is required because the dynamic
behaviour of a servo-hydraulic testing-machine is
affected by the stiffness of the test specimen.
Sensitivity to specimen stiffness poses two problems:
Firstly, the machine controller has to be re-tuned every
time a different type of test specimen is loaded.

Currently such re-tuning is done manually and
because this requires some skill, is sometimes done
badly. Secondly, even if the machine controller is
correctly tuned at the start of a test, stiffness changes
during the test prevent optimum performance being
maintained. Such stiffness changes are common. In
metals testing for example, damage mechanisms such
as the propagation of fatigue cracks or transitions from
elastic to plastic behaviour cause the stiffness to
change. Other specimens - like automotive elastomeric
components - have an inherently non-linear stiffness
characteristic.

How a stiffness change affects the testing machine
depends upon the mode of control used for the test. In
load-control, the reverse happens; response becomes
sharper but this can lead to closed-loop instability - see
figure 2.
Sensitivity to stiffness change depends on the fixed stiffnesses of the hydraulic actuator and load-frame. The load-frame is designed to be stiff to minimise the strain energy stored when the specimen is loaded. Actuators, on the other hand, come in all shapes and sizes to suit varied requirements of speed, force and stroke. Sensitivity is worst in load control if the actuator is stiff. In strain control, machines fitted with soft actuators tend to be most affected.

**What has already been done by others**

The following chronological list is published information that I have managed to track down:

**1992** PID self-tuning controller


This controller used to be marketed by Carl Schenck GmbH. It uses an impulse signal to determine system dynamics. A hill-climbing optimisation routine is then employed to find the best set of PID parameters. The method is principally aimed at initial auto-tuning. Fromme suggests that it could be used during testing to re-tune but this would involve applying more impulses.

**1986** Adaptive control of amplitude and frequency

P. R. Edwards, *Control and monitoring of servo-hydraulic fatigue machines using a computer network with adaptive control of amplitude and frequency*, Measurement and Fatigue - EIS'86 (published by EMAS), pp.3-17, 1986. This is an outer-loop control scheme for improving the turning point accuracy of variable amplitude loading during fatigue testing. It is a learning controller which makes demand signal adjustments based upon the errors recorded the last time the test sequence was applied. It only looks at turning point accuracy. Traverses from one turning point to the next are not monitored. Only the demand signal is modified. The fidelity of the primary feedback loop remains uncorrected.
(1989/90) Pole placement self-tuning control


This work was conducted at the Ohio State University using equipment donated by MTS. The stated aim of the work was to develop a self-tuning controller for servo-hydraulic materials testing machines which did not have to be manually tuned by the sort of trial and error approach used on existing PID controllers. After several investigations, a pole-placement controller was adopted. Trials on a real machine worked well as long as the demand signal was dynamically rich. Work concentrated on self-tuning. In-test adaptive control was not tried.

(1990/91) Repetitive control


Repetitive control - mainly developed in Japan for systems with periodic inputs - has been applied to materials testing by the above two researchers. This is another learning type of controller with cycle reduces errors caused by non-linearities. It is only suitable for periodic waveforms.

The above methods can be classified as self-tuning or complementary controllers. Non though satisfies the general requirement for adaptive control. The complementary learning controllers are specific to particular demand signals and types of test and to extend the self-tuning methods to cope with stiffness changes requires the use of unwanted probing signals to estimate dynamics. Estimation is particularly difficult in dynamically rich and probing cannot be tolerated during many material tests.
Advantages of the Instron Adaptive control scheme

In contrast to the earlier schemes listed in the last section, the Instron adaptive controller described in the next section has the following advantages:

- A tuning experiment is not required every time a different type of specimen is loaded in the testing machine. The machine operator simply loads the new specimen and, without applying any special signals, the adaptive algorithm makes the necessary changes to the controller.

- Stiffness changes that occur during a test are compensated for without the use of probing signals. This is possible even when the test signals are not dynamically rich.

- Rapid stiffness changes can be tracked more responsively.

These advantages stem from the fact that a physical model of the testing machine is used to formulate the adaptive algorithm. This means that only the parameter that is changing i.e. stiffness has to be estimated on-line. Other methods follow the classic black-box approach where reasonable dynamic order is the only structural information that is pre-specified. The physics that govern machine behaviour are completely ignored. This is why such schemes tend to be slow and require probing if the normal operating signals are not very dynamic.

How the Instron adaptive algorithm works

Figure 3 is a block diagram of the adaptive controller. In the lower part of the figure is the normal feedback control loop consisting of the PID controller, the servo-valve, actuator and the test specimen. Control mode (position, load or strain) is selected by the mode selection switch which chooses from the transducer signals an appropriate feedback signal.

Adaptive control is achieved by modifying the PID controller terms according to real-time estimates of the specimen stiffness and the combined stiffness of the specimen and frame. These estimates are obtained from the position, load and extension signals by the stiffness estimator shown at the top of figure 3.

The relationship between the PID terms and stiffness is not the same on all machines. The relationship for a particular machine is defined by the machine-model. This represents mathematically the current dynamics of the actuator, load frame and specimen combination. Its
parameters are constituted from the two time varying stiffness estimates plus time-invariant terms called **start-up parameters** which, although fixed, are different from machine to machine.

The start-up parameters are determined in a **once-only** experiment by the **commissioning parameter estimator** when the machine is first built. Small amplitude square-wave signals are used to perturb the actuator so that these fixed terms can be identified. During subsequent operation, the machine-model only needs to be updated by the stiffness estimates to accurately reflect any changes in machine dynamics.

The **controller design** stage is the part of the adaptive controller which actually changes the PID terms. It does this according to a test specification using information about machine-model. The requirement for most tests is that the loop gain should be as high as possible without producing significant square-wave response overshoots.

**Adaptive control example**

Adaptive control makes the testing machine insensitive to specimen stiffness changes. Performance is maintained as it was when the system was first commissioned. This is demonstrated by the low cycle fatigue (LCF) test result shown in figure 4.

During an LCF test the test specimen is cycled at an amplitude which exceeds the elastic limit of the material. Cycles therefore exhibit portions of both elastic and plastic strain. The stiffness of the test specimen is continually changing with abrupt changes at each strain reversal. The result shown in figure 4 was conducted in strain control at a frequency of 1Hz. The two cycles shown have been artificially stretched in the strain direction when plotted so that they can be separated. The two loops would otherwise be superimposed. Increasing time is indicated by the arrows.

Oscillations can be clearly seen in the plastic region at the start of the test record where adaptive control was switched off. They are caused for the same reason as the oscillations of figure 2 - namely that in strain control the loop gain increases when the specimen yields.

When adaptive control was switched on the oscillations disappeared. This demonstrates the usefulness of adaptive control. Oscillations in the plastic region often frustrate LCF testing. Without adaptive control, they can often only be prevented by reducing the controller gain. Such action though has the bad side-effect of degrading performance when the specimen is elastic and at strain turn around.

**Implementation**

The Instron adaptive controller runs on an upgraded version of Instron's 8500 direct digital controller for servo-hydraulic materials-testing machines due to be launched later this year. This is a multi-processor platform. Code resides in firmware. Real-time tasks such as stiffness estimation, the PID controller and PID updates are performed by a TMS320C31 floating-point arithmetic processor and logic unit. Non real-time tasks such as determining the start-up parameters are performed by a MC68340 32-bit CPU with peripheral devices.

![Load vs stretched-extension](image)

**Fig. 4** LCF test result showing how adaptive control prevents instability during plastic straining.