

**CPM8.1 Task 4:
The Measurement of
Blocking Force**

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ABSTRACT

The modulus and blocking force characteristics of multilayer ceramic actuators have been measured using a novel measurement method based on the computer-controlled application of a continuous range of external loading stiffness constraints. The full blocking force graph may be deduced which exhibits substantial departure from the previously presumed linear measurements and calculations. This is useful design data for actuator designers and users.

1 INTRODUCTION

Piezoelectric multilayer actuators have found a wide range of applications owing to their low voltage drive requirements (compared to bulk materials), rapid dynamic response, high and accurate actuation strain and large generative forces that may be realised [1-4]. The multilayer actuator typically consists of many hundreds of layers of piezoelectric ceramic separated by conducting elements wired in parallel using interdigitated electrode techniques. Sometimes the sandwich is glued and sometimes fired in a furnace to produce the rigid actuator. A significant amount of research has been carried out in the design [5] processing [6,7] and characterisation [8-19] of multilayer actuators and excellent devices are now available commercially, appendix II.

A particular characteristic of actuators that has not been explored in great detail is the relationship between strain and actuation force. When the actuator is operated without any applied load then the strain observed may be measured easily and this value of strain is often referred to as the free displacement, or the maximum displacement. If the actuator is placed within a perfectly un-yielding clamp then, although a large force may be exerted, there is zero strain and zero displacement. The performance of the actuator between these two extremes is the subject of this measurement note, that is the measurement of the 'static' mechanical properties of the actuator within *controlled* mechanical constraints.

1.1 ACTUATION REQUIREMENTS

The practical application of piezoelectric actuators requires knowledge of many specific factors including:

- Maximum displacement required
- Maximum force exertion required (e.g. to operate or move another component)
- Frequency of operation
- Lifetime requirements and fatigue mechanisms
- Temperature for in-service and non-use operation
- Static and dynamic loads required
- Loading mechanism, method used to load and operate the actuator
- Any other environmental constraints such as use in vacuum and humidity

These design constraints must all be factored into the choice of actuator material, design concept, electrode configuration, conformal coating, power supply, external components etc. The multilayer actuator is typically operated at far higher electrical fields than most other applications that utilise piezoelectric materials, resulting in significant non-linear output. To carry out such design and materials selection, the materials linear *and* non-linear properties must be known and understood. Although some materials data are known there is a lack of creditable design data that satisfies this rather long list of requirements.

The maximum force a piezoelectric actuator may exert depends on many factors, the first of which must be related to its own compressive strength. In reality, this is hardly ever achieved

but certainly sets limits on the pre-stress that must be applied across the entire dynamic range so that the actuator always operates in compression. The ultimate compressive strength depends on ceramic failure stress and other component failure such as electrode breakdown, buckling of actuator, edge fracture etc. A more significant and relevant aspect that limits force application arises from the fact that piezoelectric materials degrade under excessive mechanical stress via depolarisation mechanisms, leading to a loss of piezoelectric activity and hence actuation performance. Additionally, generally both tensile and shear forces must be minimised (since ceramics and these structures are comparatively weak in these modes) by the use of adequate prestress and linear motional guide mechanisms.

Domain switching (reversible) is predominantly responsible for non-linear behaviour even at the lowest stresses. Additional non-linear effects are observed at high electric or mechanical fields when irreversible domain switching (ferroelectric and ferroelastic) causes depolarisation of the ceramic. The impact of ferroelastic switching at high mechanical fields is to reduce the apparent elastic modulus of the material, which will manifest itself as a reduced actuation force [8]. Similar implications are noted for high electric field induced non-linear properties in piezoelectrics. The movement of ferroelectric domains is a lossy process that gives rise to the non-linear behaviour and hysteresis. Both electrical drive and mechanical drive impose sometimes-severe limitations on the operational envelope of the actuator - ultimately to avoid over-heating, dielectric breakdown, mechanical depolarisation and other physical energy losses. In fact, even at modest drive levels, the non-linear hysteretic properties of soft materials means that piezoelectric actuators must be driven using a displacement feedback system to enable linear operation. The variation in piezoelectric activity with frequency (another non-linear artefact of the microscopic mechanisms operating within the material) must also be considered when designing the actuator. Models based on non-linear viscoelastic materials have been developed to help provide closed-loop control algorithms for ultra-precision positioning systems [10]. The static response may be measured using the system described in this report and modelled using fairly simple compliance equations. The dynamic (high frequency) response is fundamentally determined by the drive waveform (shape and period), frequency, drive levels and materials and systems losses.

Component stiffness', such as the ceramics, electrodes and any external structure attached to the actuator, must be taken into account in the design of actuators. For example, piezoelectric resonant frequency, force generation and dynamic response all depend in some way on component stiffness. For solid materials, stiffness is proportional to the elastic or Young's modulus and is often described by a spring constant, k , that describes displacement under an applied external force. For piezoelectric materials the situation is more complex owing to the inherent non-linear elastic behaviour [20, 21] such that linear stiffness is only appropriate for small signal force/motions. Additionally, the complexity of piezoelectric materials confers a similar complexity in the measurement of their properties! An example is the materials modulus, measured typically by applying a known mechanical stress and measuring the resulting strain. In piezoelectrics the value of stiffness or modulus calculated is affected by the exact measurement method according to the whether the material is measured in:

- Static or dynamic conditions
- Open circuit or short circuit conditions

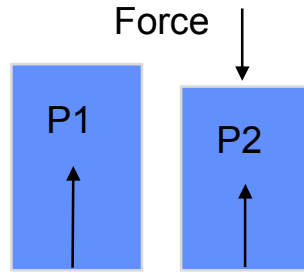


Figure 1: Change in strain following change in polarisation

Piezoelectrics are poled materials with a remanent strain that depends on the materials polarisation, P . As the material is mechanically compressed the strain contraction depends on the materials intrinsic stiffness and its own change in polarisation, from $P1$ to $P2$, (following from a change in remanent strain), figure 1. Generally, this change in polarisation - depolarisation - follows the form taken by the non-linear stress/strain response, and is linked to stress induced ferroelastic domain switching [18, 22, 23]. As previously described, this depolarisation will act to reduce the material's apparent stiffness and hence force generating capacity.

The direct piezoelectric effect describes the electric charge liberated when a piezoelectric material is mechanically compressed. If the electrodes are left open-circuit (constant dielectric displacement, D) then charge starts to build up at the electrodes that in turn generate an internal force counter to the external stress. An interesting physical interpretation is that each volume of material, experiencing a dimensional change from the compressive stress will build up a charge across all its surfaces, giving rise to an internal polarising field across it. This field, via the converse piezoelectric effect, will generate a strain that acts to oppose the external stress. This has the effect of increasing the materials effective stiffness. Another way of looking at the situation is that the induced field opposes the switching (motion) of non- 180° domains. This reduces their contribution to the strain and therefore makes the material appear stiffer and less non-linear. The open circuit experiment may be described by the following equation, *with the value of D set equal to zero*;

$D = \epsilon_0 \epsilon_r E + d \sigma$ with E =electric field, ϵ_0 = permittivity of free space, ϵ_r = relative permittivity, d = piezoelectric strain tensor and σ =stress, then a change of D produced by the direct piezo effect (stressed sample) must be balanced by an equal and opposite D produced by an induced electric field.

Measurements under short-circuit conditions (constant electric field, E , such as when driven by a low output impedance power amplifier) are not affected by charge build-up, since there is a path for the charge to flow and cancel and the measured stiffness is lower. So, modulus measurements must take into account for example dc bias fields (for electrostrictive materials for example) and non-linearity in σ , E , etc. The modulus of typical multilayer actuators has been measured using the experimental equipment designed for blocking force measurements, described in this report.

Actuators are often used to generate displacement, but piezoelectric ceramic materials can also generate substantial forces that may be used to open and close valves, deform compliant materials etc. It is instructive to investigate the differences between static dead loads and

dynamic or changing loads characteristic of a spring, since the two confer very different loading constraints on the actuator.

Case 1: Constant Load/Force

An actuator responds (ideally) to an applied electric field with an extension according to figure 2. In reality the displacement is neither linear nor unhysteretic but for this description this will be overlooked. When a mass is applied on top of an actuator the ceramic will be compressed slightly according to its own stiffness. Increasing the electric field from zero volts will extend the piezoelectric by the same relative amount as before, figure 2. (ΔX_0 is constant). That is the piezoelectric actuator will compress when a mass is applied and any piezoelectric motion will simply be offset by the stiffness of the piezo.

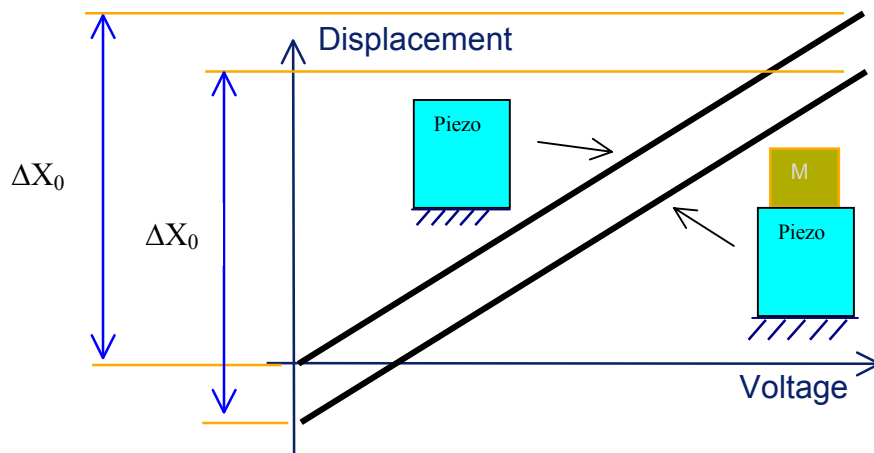


Figure 2: Effect of static mass on actuator response

Now consider the case where the piezoelectric actuator is pushing against a spring force such as opening and closing a valve.

Case 2: Spring Forces

Again, assuming ideal linear piezoelectric behaviour the piezo will respond to applied electric field according to figure 3. As the actuator extends under the action of an electric field it will experience an increasing restoring force exerted on it by the spring, leading to a reduction in total displacement, $\Delta X_1 < \Delta X_0$.

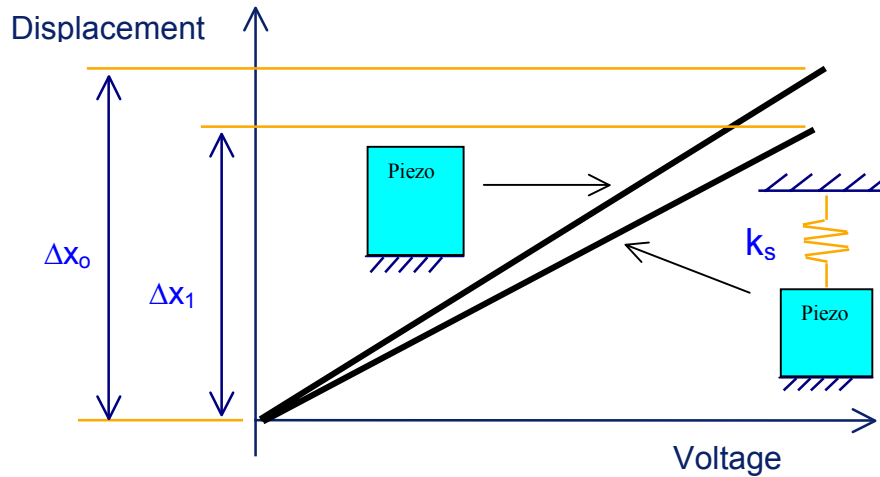


Figure 3. Effect of spring load on actuator response

This behaviour is clearly different to the static load example and is the more realistic loading environment for actuators. Typically, an actuator would be required to operate a valve that may be spring loaded or may be constrained within a clamping system. The displacement of piezoelectric multilayer actuators is typically $1\mu\text{m}$ per 1mm of actuator ceramic at near maximum electrical drive voltages (typically 150 V_{pp}). When the actuator is constrained within a clamp having an appreciable stiffness then this displacement is necessarily reduced, as already described. The application of a variety of clamping stiffness may yield the actuators response from the zero loading situations to fully clamped. If a very large number of different stiffness springs are used, k_{s1} , k_{s2} for example, and the force – displacement measured then the graph in figure 4 may be drawn. Here, the intersection of the k_{s1} or k_{s2} load line with the actuator Force-Displacement curve represents the actuators maximum displacement for that spring stiffness. This is purely an ideal case, since such measurements are not routinely carried out. Rather, only ΔX_0 is measured and then F_{max} calculated based on modulus and ΔX_0 . F_{max} is known as the **blocking force** – the maximum *force generating capability* of the actuator.

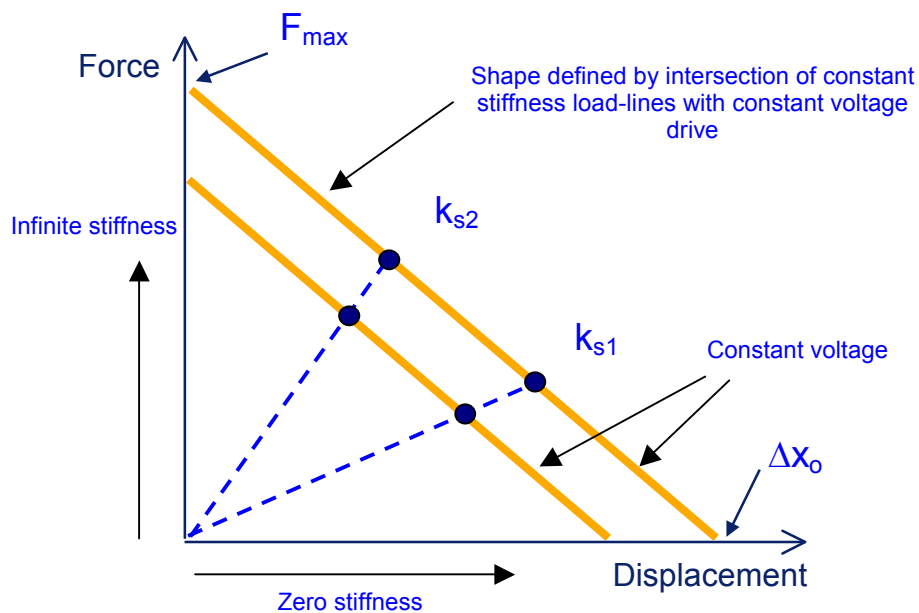


Figure 4: Construction of the blocking force diagram

Clearly, the actuator may withstand much higher static loads (until piezoelectric depolarisation is reached) but the *force generating capability* is governed by the *stiffness of the loading system*. In this work a novel system has been devised whereby the spring stiffness may be changed in real time by a load or displacement feedback linear motor that is driven to push on the actuator. Additionally, the elastic modulus (stiffness) of the actuator may also be systematically studied with regard to open/short circuit conditions.

2 EXPERIMENTAL THEORY

In many applications an actuator is not simply pushing against a static load, but maybe installed in a loading train where the actuator must fight against some sort of spring. In the static case the load is applied *before* application of the voltage, so that the effect of the load is simply to shorten the sample, which then extends in the normal way under the piezoelectric effect, as described in the last section.

For a spring load, the load is not produced until the voltage is applied and the sample expands, so the load is added *after* the voltage application. The function of the spring is simply to produce an ever-increasing load based on a spring constant k_s . There is nothing special about using a spring and any loading mechanism can be used to mimic this function, i.e. a load that is dependent on the length of the spring.

Consider an experiment where we apply a stepwise voltage to a piezoelectric sample but after each step we apply an ever-increasing load, which mimics the effect of a spring.

Let x_0 be the change in sample length due to the application of a voltage, V , under no load conditions, and let k_s be the spring constant for the artificial spring loading system. Then, after application of a voltage V , the sample extends x_0 and so we must apply a load based on a spring constant k_s :

$$\text{Load} = x_0 \cdot k_s \quad (1)$$

The application of this load now changes the sample length by

$$\text{Displacement} = x_0 - \text{Load} / k_a \quad (2)$$

where k_a is the stiffness of the actuator.

In fact, the artificial spring is not exactly the same as a real spring as we have assumed that when the actuator extends x_0 , all this displacement is taken up by the spring, whereas in a real spring loading system the displacement is *shared* between the actuator and the loading spring. This simply means that there is a modification to the spring constant that we use in equation (1). The effective stiffness of this system is given by the load-displacement behaviour defined by (1) and (2), so the effective stiffness of the artificial spring system is now

$$k_{\text{eff}} = x_0 \cdot k_s / (x_0 - \text{Load}/k_a) = k_s / (1 - k_s / k_a) \quad (3)$$

When $k_s = 0$, then $k_{\text{eff}} = 0$, this is obviously the free displacement.

When $k_s = k_a$, then $k_{\text{eff}} = \text{infinite}$, there is no displacement and this is the fully blocked case.

When $2k_s = k_a$, then $k_{\text{eff}} = k_a$, this is the special case where the spring constant of the loading system is equal to the actuator stiffness, and corresponds to half the no-load displacement. Remember, if a *real* spring were used then we must use the value of k_{eff} to describe the stiffness of our real spring. In our experiments we are only able to calculate the value of k_{eff} *after* the experiment has been completed (by measuring the gradient of the force/displacement curves) *unless* we have already measured the stiffness of our actuator k_a . This spring analogy has been implemented in the blocking force system described in the next section.

3 EXPERIMENTAL SYSTEM

A variable stiffness jig has been designed and constructed, based on the description given in section 2, so that elastic modulus measurements may be taken and the full blocking force characteristics may also be measured. The latter is afforded by the computer control of a 'simulated' external structure having stiffness values ranging from zero up to essentially infinite stiffness that is imposed on the actuator. Displacement has been measured using strain gauges attached to the actuator in three different positions around the faces of a square section sample and load measured using an in-line resistive load cell and bridge amplifier. Displacement and load have been measured as a function of applied electric field for differing simulated values of stiffness. The system is schematically illustrated in figure 5.

Stiffness variation is afforded by use of a D.C. motor, gearbox and ball-screw that converts the rotary motion to linear. This is coupled to the actuator sample through a compliant coil-spring. Alignment is provided by the use of a ball bearing loading point and dual bearing linear ball-guide. Strain is measured using strain gauges bonded to the actuator using cyanoacrylate adhesive and a $\frac{1}{4}$ bridge strain gauge amplifier. The strain resolution is currently limited to 12 bit for full range of output yielding a value of approximately $\pm 1\mu\text{strain}$ or $0.02\mu\text{m}$ for a 22 mm actuator. Load is measured using a strain gauge resistive load cell with load resolution of approximately $\pm 1\text{N}$ (again limited by the choice of computer A/D card). The D.C. motor drive is operated using a commercial PID controller running in load control for these experiments. The motor's tachometer output is used as velocity input to the PID controller.

The sample is placed under a small prestress using software motor advance routines. The user then selects an external spring stiffness, k_s . The actuator modulus may also be measured using the modulus function written within the software. As the electric field is applied to the sample the computer continuously monitors its extension. At incremental levels of voltage the computer instructs the motor to compress the sample by an amount that the simulated spring would have done.

This compression counters the piezoelectric extension of the actuator, i.e. it blocks some of the piezo-extension. The voltage is incremented again and the process of partial blocking repeated. The user can instruct the software to increment the simulated spring stiffness to cover the entire range needed to construct a blocking force diagram. The procedure is shown in figure 6.

The experiments are performed at different simulated spring stiffness values. These data will define the lines $0k_s1$, $0k_s2$ etc, in figure 4. Once all necessary lines are measured and drawn onto the graph then lines of *equal electric potential* may further be added to the graph. These

lines describe the blocking force load/displacement curves at different drive voltages. The curve depicted for maximum drive voltage then clearly defines the actuators maximum blocking force.

Once the various k_s values are completed and the blocking force curves $0k_{s1}$, $0k_{s2}$ etc are drawn then the effective spring stiffness may be calculated from a measurement of their gradients. From the calculated values then k_a may be backed out using the relationship given in equation 3. Alternatively, k_a may be measured independently and appropriate values of k_s may be used as input to the blocking force program.

The system prototype was manufactured at NPL using easily accessible parts and materials. Alternative materials such as stainless steel, ceramic half spherical loading points and finer pitch ball screw would improve performance. The photograph in figure 7 shows the entire system, with an enlarged view highlighting the 'loading' actuator end reproduced in the photograph of figure 8.

The computer software was written in National Instruments LabWindows CVI (a C based GUI interface package). The software requests user input detailing sample name, dimensions, maximum electrical field etc and then either a blocking force measurement can be performed or the actuators modulus measured. The front panel, although quite complicated in this prototype, enables all data to be viewed as the experiment is running, figure 9.

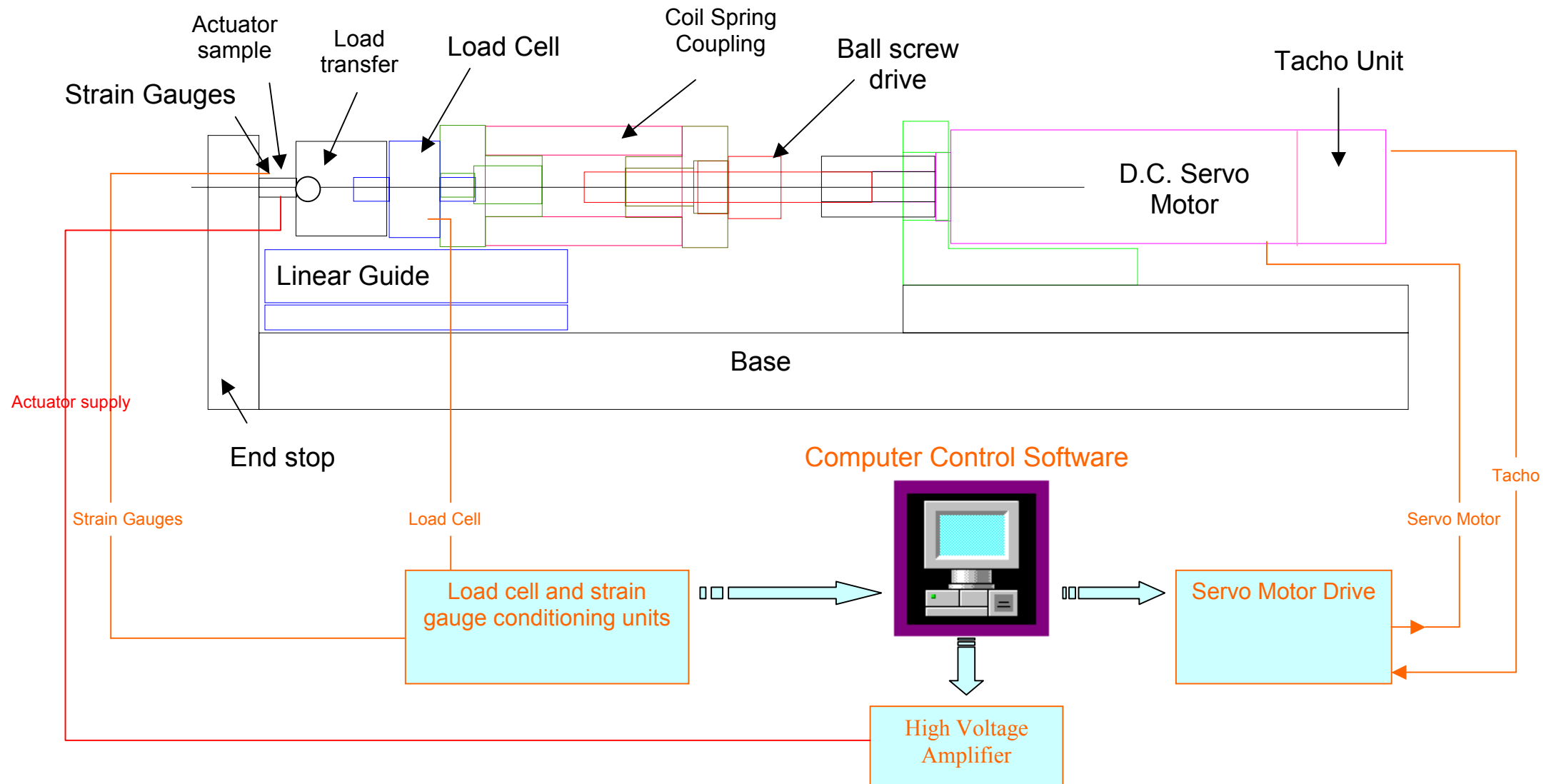


Figure 5: Scematic of the Blocking Force apparatus

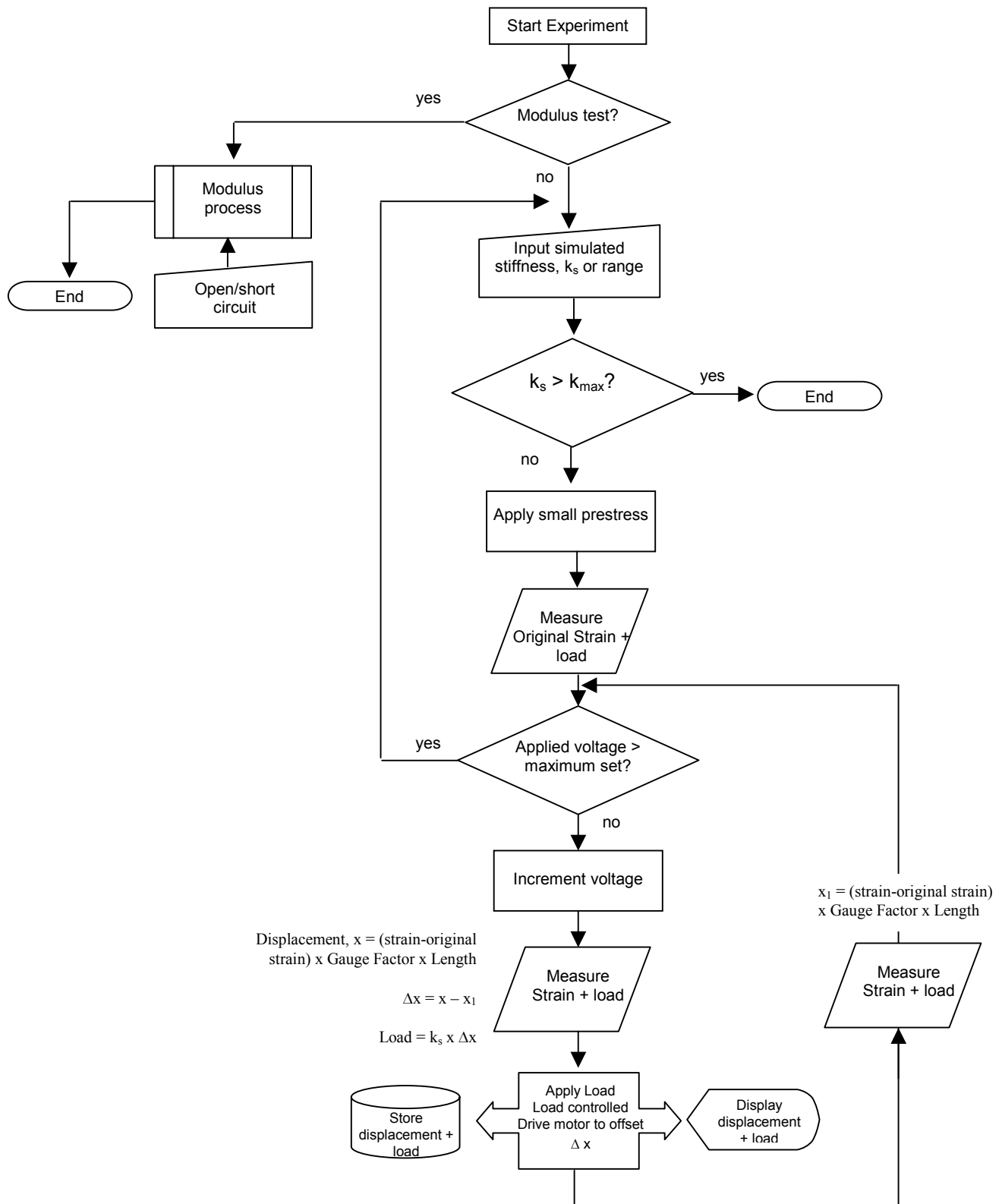


Figure 6: Blocking Force program structure

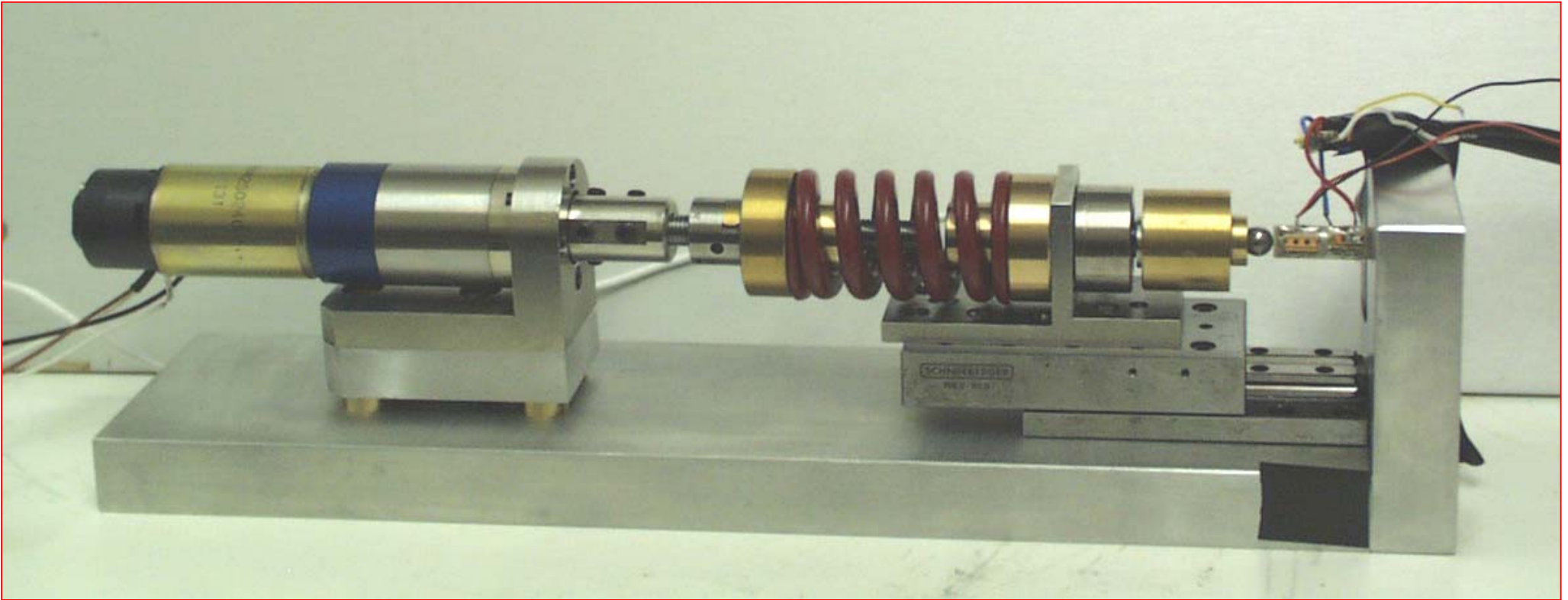


Figure 7: Photograph of the completed system

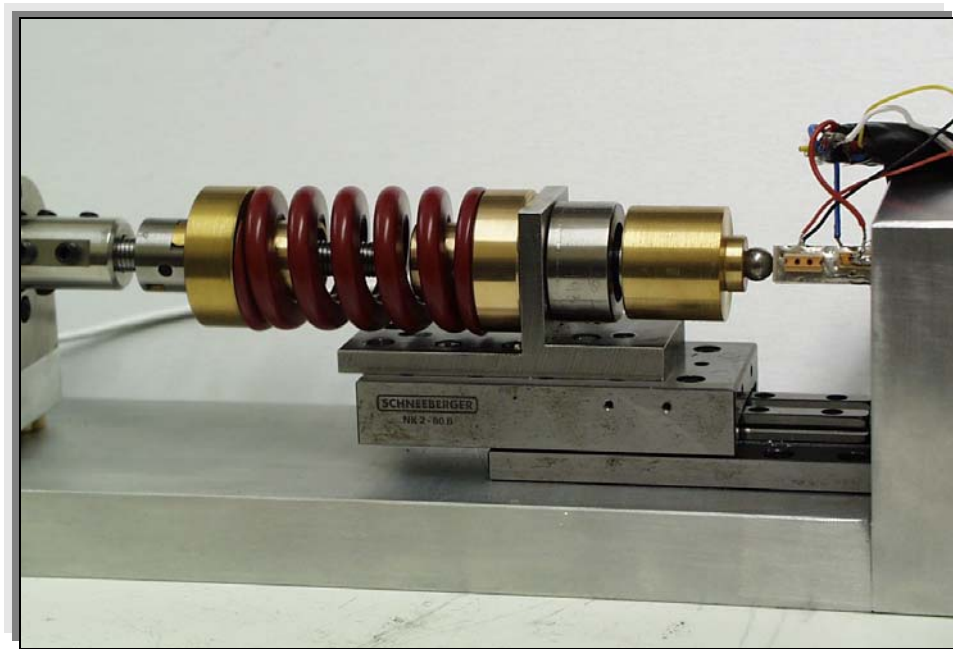


Figure 8: Enlarged photo of the load application end of the apparatus

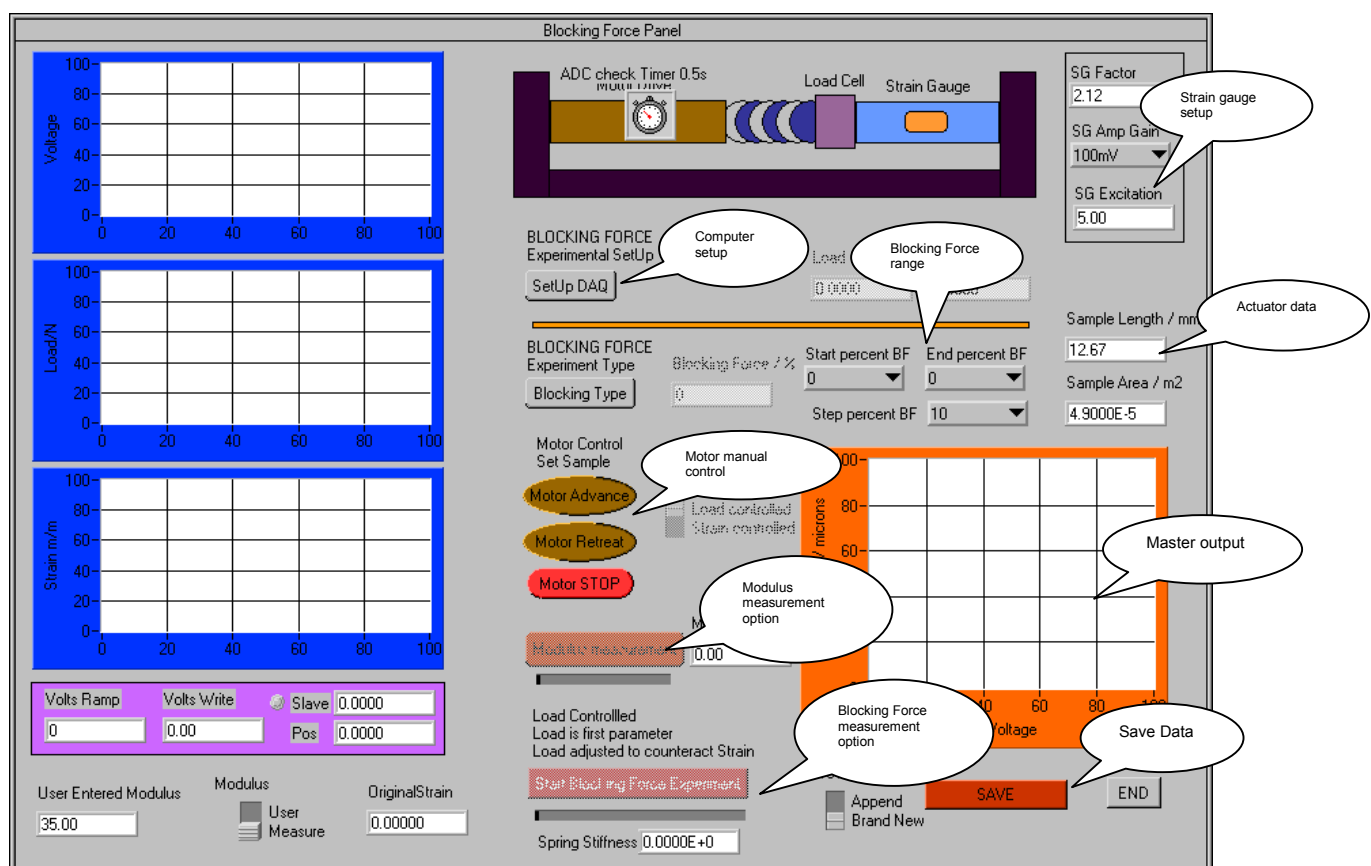


Figure 9: Front panel of the software

4 RESULTS AND ANALYSIS

4.1 MODULUS RESULTS

Multilayer actuators, 22mm long, 7mm square, were positioned between the loading faces of the blocking force system. Two experiments were carried out; one open circuit and one short circuit. It was important to confirm that the actuator drive leads were disconnected from any coaxial leads at the actuator end for true open circuit validity. Using thick electrical wire connecting the power leads as close as possible to the actuator satisfied short circuit conditions. A small load was applied to the actuator and the actuator rotated until the strain gauges all read similar values and that upon initial loading the slope of strain against load was as linear as possible. This is a good indication of any misalignment that can often occur in mechanical compressive testing [24].

The software controls the whole experiment and calculates the modulus from the material's dimensions that the user has input, figure 10. This modulus is saved and may be used for subsequent blocking force experiments. Alternatively the user may override this measured value.

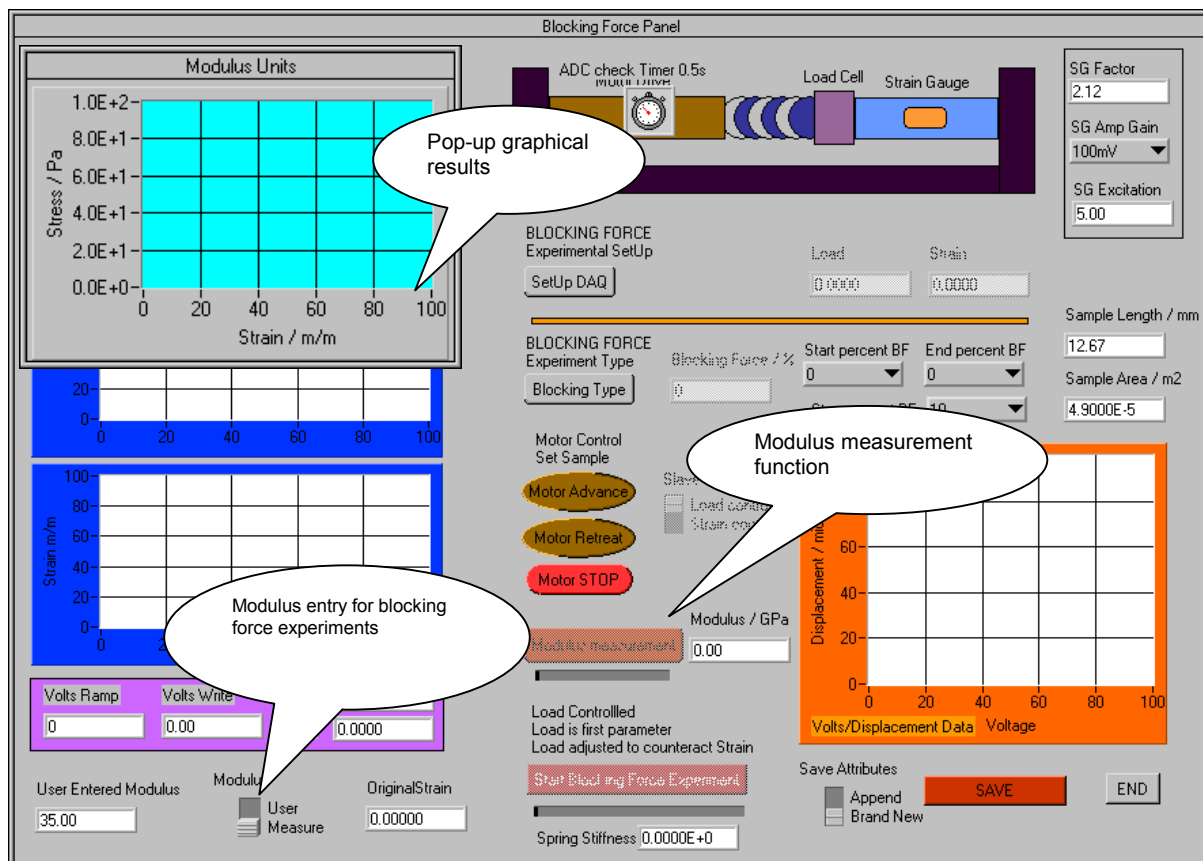


Figure 10: Front panel of the Modulus function of the program

The data in figure 11, shows the difference in modulus between these two conditions. For this actuator, the short circuit modulus was calculated as ~ 48 GPa which was approximately half

of its open circuit value, see Introduction. The short circuit value should be used for the blocking force calculations since the actuator will be operated from a low output impedance power amplifier – essentially closed circuit.

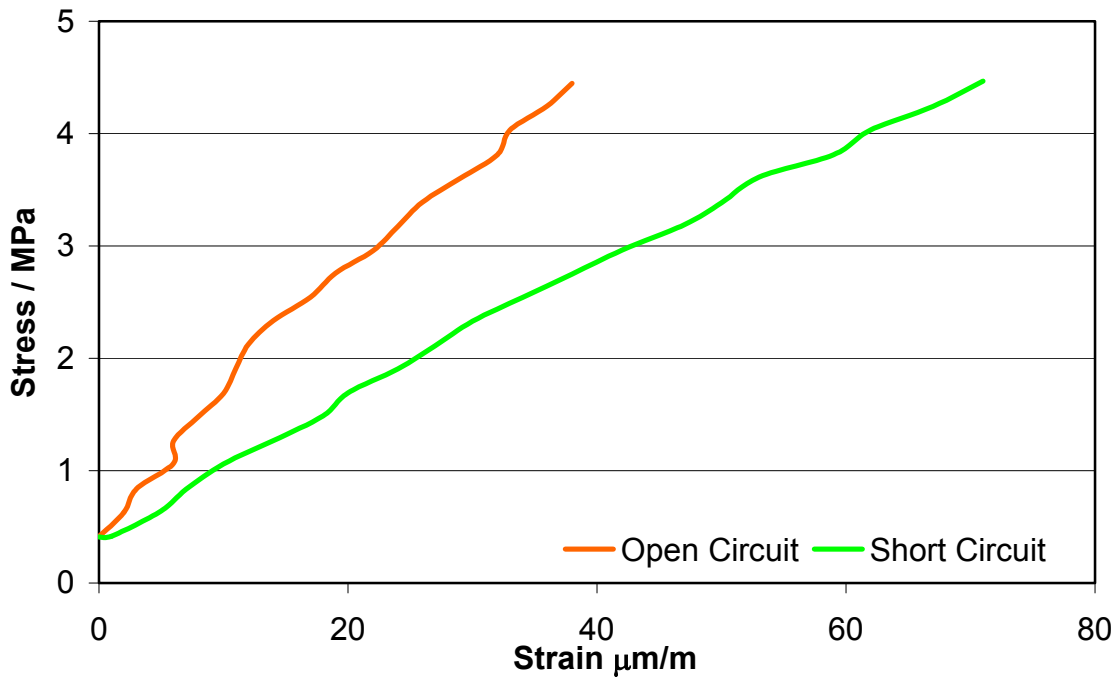


Figure 11: Modulus results for the Multi-layer actuator

4.2 BLOCKING FORCES

The blocking force measurement proceeds by applying a variable load (using the computer controlled motor) to simulate the external spring stiffness, k_s , and monitoring the actuator strain and load whilst increasing actuator D.C. drive voltage. A series of different spring rates can be applied to the actuator using this procedure and a set of curves of displacement versus voltage may be drawn, figure 12.

Plotted as a function of load and displacement we can start to generate the conventional blocking force graph. Note that the constant voltage lines are not linear, figure 13. The blocking force is defined as the maximum force the actuator can apply at zero displacement, measured at maximum permitted drive voltage. In these experiments, the maximum voltage was never applied and so the maximum blocking force was clearly not calculated.

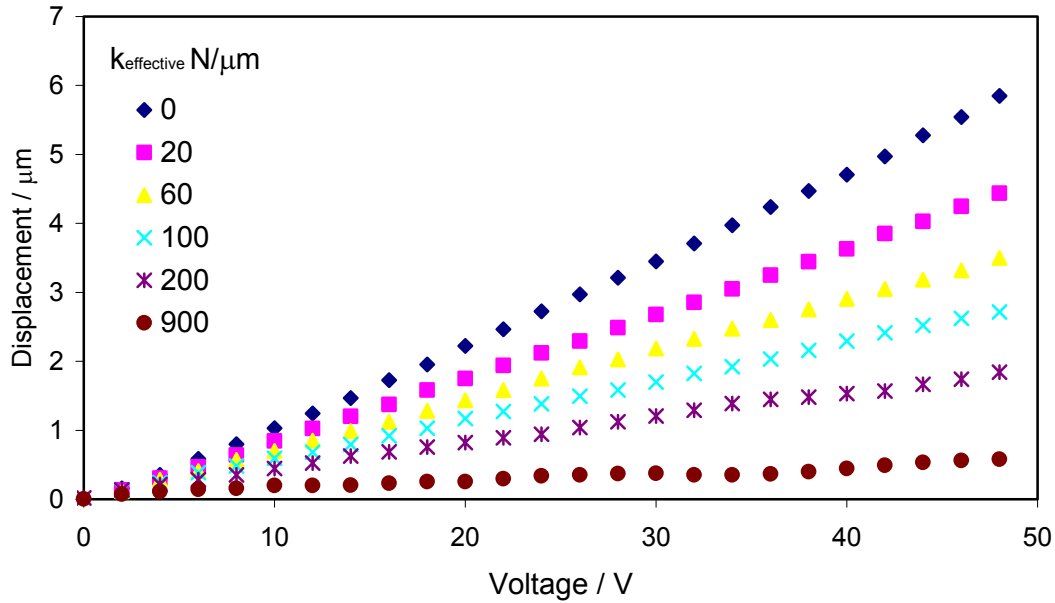


Figure 12: MLA displacement with voltage for a variety of different spring stiffness loads

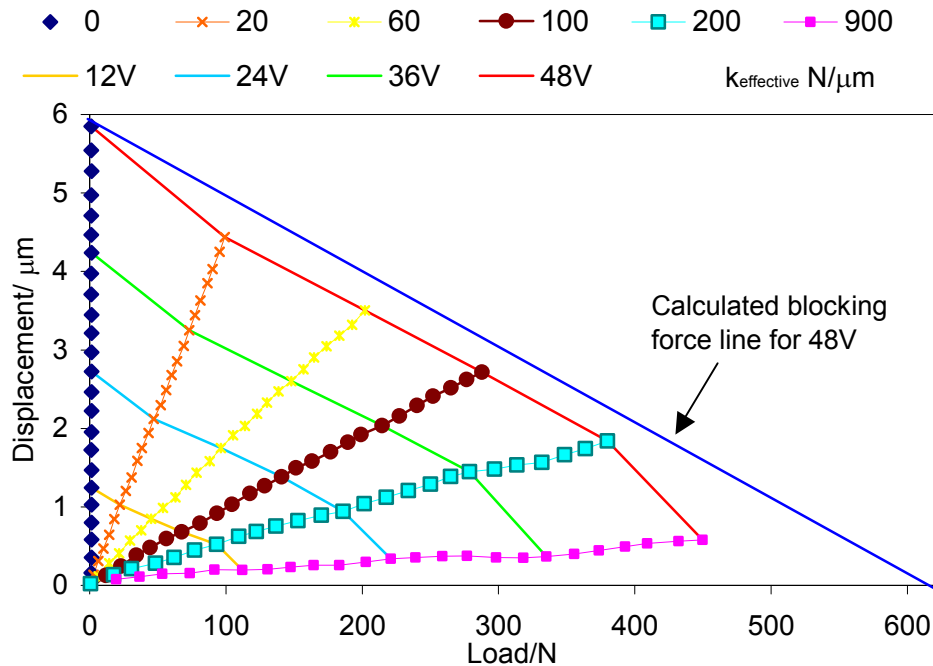


Figure 13: The blocking force graph for the MLA

The blocking force curves are *not* linear. This validates the need for this experiment and the collection of this type of data necessary for actuator designers and users. The equipotential lines all exhibit similar non-linearity between displacement and load, which is encouraging in that equations governing the performance of the actuator may be formulated to provide a continuous description of its output. It is also instructive to measure the deviation from linearity. The maximum force exerted by the actuator under zero displacement operation is calculated normally from the value of ΔX_0 and the ceramic stiffness. The ceramic stiffness is given by its modulus, E , and its linear dimensions by: $k_a = E \cdot \text{Area} / \text{Length} = 48\text{GPa} \times 7\text{mm} \times$

$7\text{mm} / 22\text{mm} = 1.07 \times 10^8 \text{ N/m}$ for the actuator used in this study. F_{max} is obtained from the maximum displacement at each operating voltage and the value of k_s . For example, the maximum voltage applied to this actuator was $48V_{\text{pp}}$. For this line on the graph (figure 13), the maximum $\Delta X_0 = 5.8 \mu\text{m}$. Substituting this into the above equation yields a value for the zero load force of approximately 620 N. This is in excess of that actually obtained and clearly demonstrates the dangers of assuming linear behaviour. For all other voltages measured in these experiments the situation remains the same.

The values of effective stiffness measured from the gradients in figure 13 reveal that the value of k_{eff} for one half the blocking force displacement corresponds to the stiffness of the actuator, as expected from the analysis presented in section 2.

The measured blocking force curve departs significantly from the calculated displacement force line in figure 13. Interestingly, the slight decrease of displacement at low spring stiffness and slight rise of displacement at high spring stiffness is a feature present for all actuators measured and for all drive voltages. The stiffness of piezoelectric materials is known to depend on voltage and stress [21]. This non-linearity would be thus expected to show itself in these and similar blocking force experiments. The piezoelectric ceramic compliance has been observed to increase with increasing mechanical stress [24], which is observed in the blocking force diagram as a change in slope of the displacement/load curves with increasing load (at constant voltage). This may explain part of the non-linear behaviour observed for these multilayer actuators. Other non-linearities are also likely to be present. The departures from linear behaviour are likely to originate from a combination of these factors.

5 CONCLUSION

The modulus and blocking force characteristics of multilayer ceramic actuators have been measured using a novel measurement method based on the computer-controlled application of a continuous range of external loading stiffness constraints. The full blocking force graph may be deduced which exhibits substantial departure from the previously presumed linear measurements and calculations. This represents useful design data for actuator designers and users.

The system may be further refined by enhancing its sensitivity (through increased computer data acquisition resolution) to accommodate measurements on monolithic ceramic actuators that typically produce extensions of an order of magnitude lower than their multilayer counterparts. The data may be collected as a function of temperature to provide additional useful design data. Better strain measurement may be accomplished through the re-design of the load application faces through the use of hemi-spherical dome loading points. Alternative electrical constraints may be accommodated such as DC bias or some dynamic low frequency measurements taken. Hysteresis may also be routinely measured.

This NPL device may be of use to actuator manufacturers and end-users.

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APPENDIX I: SUPPLIERS OF EQUIPMENT

Please note that there are many other suppliers for the components needed to construct such a blocking force system. The suppliers that NPL used are listed below.

Motor and Motor Controller

McLennan Servo Supplies Ltd, Camberley, Surrey, UK.

<http://www.mclennan.demon.co.uk/>

Servo Controller: Type PM 121-37

Motor: Minimotor SA, swiss made, 30/1, 246:1

Ball lead-screw

Automotion International Ltd, Oldham, UK.

<http://www.automotion.co.uk>

Linear bearing table

Schneeberger, Tel 0162 5827708, Fax 01625827780, E-Mail info-uk@schneeberger.com

<http://www.schneeberger.com/>

Type NK2 – 80B

Springs

Springmasters Ltd, Redditch, UK.

<http://www.springmasters.com/>

Load cell

RDP Electronics Ltd, Wolverhampton, UK.

<http://www.rdpelectronics.com/>

RDP Load cell Transducer Indicator type E308

Strain Gauges

Tokyo Sokki Kenkyujo Co. Ltd., TOKYO, 140-8560 JAPAN

<http://www.tokysokki.co.jp/e/index.html>

Type FLA-6-11

Strain Gauge amplifier

Fylde, Preston, Lancashire, UK

<http://www.fylde.com/>

Type 359TA Transducer amplifier

PC Card

National Instruments, Newbury, Berkshire, UK

<http://www.ni.com/>

Type PCMCIA Card DAQCard 1200

Software

National Instruments, Newbury, Berkshire, UK

<http://www.ni.com/>

Lab Windows CVI ® software

NPL written software © NPL

APPENDIX II: SOME COMMERCIAL SUPPLIERS OF ACTUATORS

APC International	http://www.americanpiezo.com/
AVX Kyocera	http://www.kyocera.com/
	http://www.avxcorp.com/
Burleigh	http://www.burleigh.com/
Channel Industries Inc.	http://sonatech.com/index.htm
Ceramtec	http://www.ceramtec.com/
CTS Corporation	http://www.ctscorp.com/
Ecertec Ltd	http://www.ecertec.com/
Edo Corporation	http://www.nycedo.com/edocorp/index.html
EPCOS	http://www.epcos.com/index_e.html
Queensgate	http://www.nanopositioning.com/
Lockheed-Martin	http://www.lockheedmartin.com/
Morgan Electroceramics	http://www.morgan-electroceramics.co.uk/
Materials Systems Inc	http://www.matsysinc.com/
Piezosystem jena GmbH	http://www.piezojena.com/
Piezo Kinetics Inc	http://www.piezo-kinetics.com/
Physik Instrumente (PI)	http://www.physikinstrumente.com/
PZTech	http://www.pztech.dk/
Xinetics (USA)	http://www.tiac.net/users/xinetics
Murata	http://www.murata.com/
TDK	http://www.tdk.co.jp/tetop01
Matsushita Electronic Components	http://www.maco.panasonic.co.jp/
Toshiba ceramic	http://www.tocera.co.jp/indexe.html
NGK-NTK	http://www.ngkntk.co.jp/
Tokin	http://www.tokin.com/
Hitachi Metal	http://www.hitachi-metals.hbi.ne.jp/english/index.html
Chichibu-Onoda Cement (Japan)	http://www.taiheiyo-cement.co.jp/english/index.html
Siemens	http://www.siemens.com