# MEASUREMENT OF IMPEDANCE CHARACTERISTICS OF COMPUTER KEYBOARD KEYS[1]

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*The aim of this project is to gain a more complete understanding of the tactile "feel" of computer keyboard keys by quantifying their mechanical impedance. To achieve this goal, a computer-controlled test rig that can measure computer key displacement, velocity, and contact force has been designed, constructed and tested. This paper describes the hardware and software configuration, including the data acquisition method and motion control system. Preliminary results show that the key dissipates energy during a depression-return stroke, indicating the presence of damping.*

## 1. INTRODUCTION

Based on their underlying mechanisms, which exist to provide the necessary compliance and toggling action for a typist, two types of computer keyboard keys are commonly used: rubber-dome and coil-spring keys. As indicated by their names, a rubber-dome key has a rubber dome under the keycap whereas a coil-spring key has a coil spring under the keycap. The electrical contact switch for circuit closure is located below these mechanisms in both types of keys. From a user's perspective, the rubber-dome and coil-spring keys feel different. The properties of a rubber-dome key are based on the material, the thickness and the size of the rubber dome. The coil-spring key properties are related to the spring constant (itself a function of the spring material, the spring wire diameter, and the coil diameter) and the spring free length. A user may prefer a keyboard with a certain type of key claiming it "feels right"; there are important ergonomic implications, since the "right" keyboard is one that causes less muscle fatigue and discomfort after hours of typing.

Although prior research has investigated key layout (Kroemer, 1972) and keyboard shape (Marklin et al, 1999; Simoneau, et al, 1999), studies of key tactile feel have been limited to static properties only. The tactile feel is elusive because our kinesthetic sense is a composite of several mechanical factors, both static and dynamic, that are not easily isolated nor characterized, and the kinesthetic sense is a *gestalt* sensation. Our inability to isolate mechanical properties of keys may explain why we prefer some keyboards but cannot articulate our reasons well.

Depressing a key results in an overall tactile sensation. In part, this sensation or feeling can be quantified by determining the key's mechanical impedance, i.e., *(i)* the stiffness, which relates the contact force to the displacement of the key, *(ii)* the damping, which relates the contact force to the rate of displacing the key, and *(iii)* the mass (inertia), which relates the contact force to the acceleration of the key. These three properties can be found from graphs of force-displacement, force-velocity, and force-acceleration characteristics, respectively.

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The total contact force of a finger tip depressing a key can be viewed as the summation of three terms, $F_{total} = F_{stiffness} + F_{damping} + F_{mass}$ where $F_{stiffness}$ is the force contribution due to key stiffness, $F_{damping}$ is the force contribution due to key damping, and $F_{mass}$ is the force due to key mass acceleration. For the special case of linear behavior, $F_{stiffness} = kx$ with key displacement $x$ and stiffness $k$, $F_{damping} = cv$ with key velocity $v$ and damping $c$, and $F_{mass} = ma$ with key acceleration $a$ and mass $m$. In general, $F_{stiffness}$ and $F_{damping}$ are nonlinear functions of displacement and velocity, respectively, or exhibit linear behavior only over a limited region.

## 1.1. Stiffness of Computer Keyboard Keys

In prior research the stiffness characteristics of computer keyboards has been studied. Armstrong et al. (1994) and Rempel et al. (1994) measured static force-displacement curves for certain keyboard keys. In Armstrong's study, the static applied force on the keycap was determined by measuring the reaction forces between the keyboard and the underlying work surface. (This was done by placing force transducers under ends of the keyboard.) A drawback of this approach is that it does not permit isolation of the contact force between the keycap and the key. In Rempel's study, a force transducer was secured to the underside of a standard keycap.

As specified in the ISO/DIS 9241 standard (ISO, 1995) and depicted in Figure 1, there is a nonlinear relationship between key force and displacement. The ISO specifications provide detailed information related to the static force vs. displacement characteristic of keyboard keys:

*The key displacement shall be between 1.5mm and 6.0mm. For fast, accurate keying, the displacement shall be between 2.0mm and 4.0mm. The initial resistance force shall be be-*

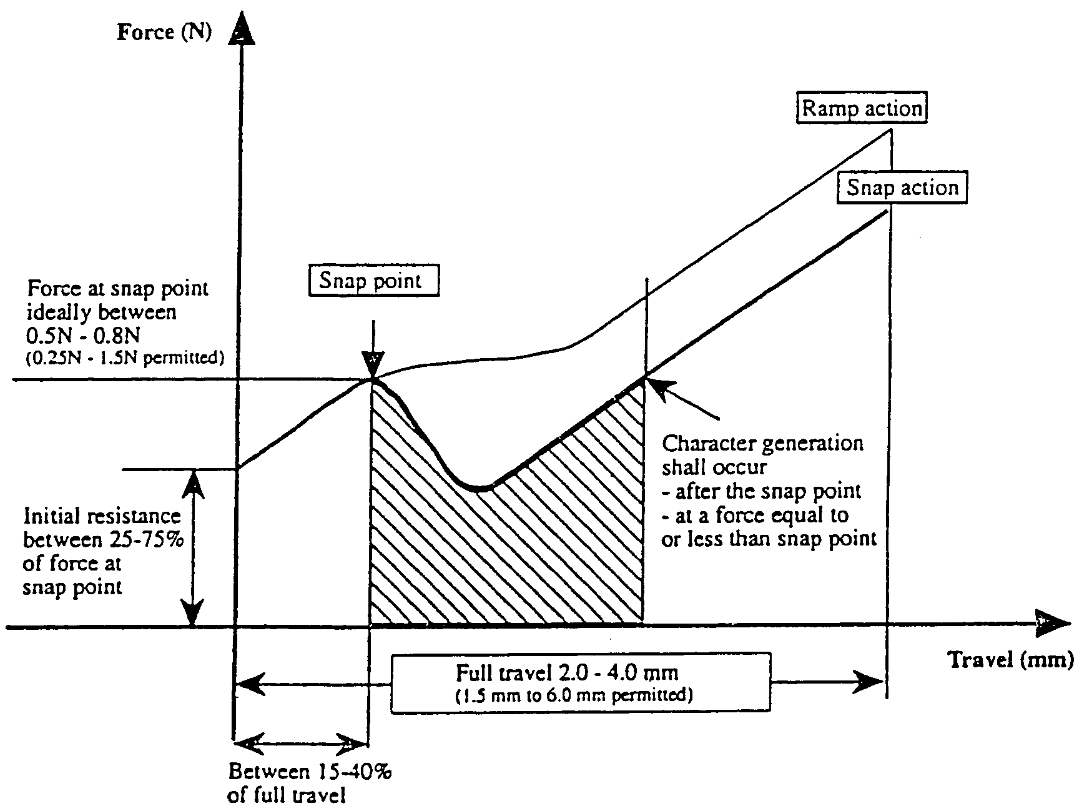


Figure 1. Relationship between key force and key displacement in ISO/DIS 9241/4.2 standard (ISO, 1995).

*tween 25% and 75% of the force at snap point. The force at the point of actuation shall be between 0.25N and 1.5N (ideally between 0.5N and 0.8N). The actuation shall occur after the snap point but before the key force has returned to the snap point force. The force vs. displacement characteristic across the alphanumeric keys shall be consistent.*

Figure 1 indicates that there are two types of force-displacement characteristics representative of keys. One type of key, “ramp action”, exhibits a monotonically increasing force as a function of travel. Another type of key, “snap action”, has a force-displacement characteristic that exhibits negative stiffness (indicated by decreasing force with increasing travel). The snap point corresponds to the displacement at which the force has a local maximum. Previous research has shown that rubber-dome keys follow the “snap action” characteristic (Gerard, 1997). Electrical actuation of the key leading to character generation occurs after the snap point at a force less than or equal to the local maximum force.

## 1.2. Damping of Computer Keyboard Keys

The effect damping plays in the operation and tactile feel of computer keyboard keys has not been addressed. Damping of computer keys may be important because typing is a dynamic activity. An individual typing at 90 words per minute (reasonable for a trained touch typist) is depressing and releasing each key in approximately 125 ms. This translates into a key velocity of 60 mm/s for a key with 4 mm travel (in both depression and return and assuming a constant velocity)[4]. Since typing is dynamic (i.e., rate dependent), key damping may be a dominant distinguishing characteristic in comparisons of keyboards.

The damping characteristics of keys may have a dramatic effect on the muscle force necessary for key activation and the resulting muscle fatigue. Since damping dissipates energy and is presumed to play a more dominant role at higher typing speeds, damping could increase the fingertip force that a typist exerts to depress a key. In a survey of studies conducted on keying forces, Gerard (1997) found that typists exert fingertip forces 2 to 8 times greater than the “make force” necessary to activate the key. The damping characteristics of the keys studied in Gerard’s survey may have accounted for some of the wide range (2× to 8× of make force) of recorded forces, since higher damping requires more fingertip force to dissipate imparted energy.

Typists exert low force levels when depressing keys (typically 10% of maximum voluntary contraction of finger flexor muscles in the forearm). The extra force required due to damping could possibly subject typists to work-related musculoskeletal disorders (WMSDs), such as carpal tunnel syndrome or tenosynovitis, because of the sheer number of keying repetitions, which can approach 100,000 key strokes per day (Kroemer, 1972). In addition, the extra force due to damping could lead to low levels of muscle fatigue in the forearm flexor and extensor muscles. Certainly, some damping is desirable to dampen unwanted oscillations of the key.[5] A high level of damping is not desirable, since it would make the key force greater during fast keystrokes. However, there may be a range of damping that offers optimal tactile feedback to a typist.

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[4] An individual can type W words per minute. An average word has 5 characters. Hence the individual types 5×W/60 characters per second. The time needed for typing one character is then 12/W second, which is the total time for the key being depressed and returned. Assuming the time a key is depressed is half of the total time, the key down time is 6/W s. The distance a key travels from its rest position to the end of travel is S mm. As a result, the average velocity a key goes down is S×W/6 mm/s. For a value for W of 90 words per minute (reasonable for a fast typist) and a value for S of 4 mm, the average velocity that a key travels is 60 mm/s. This calculation agrees with the results found by Rempel et al. (1994). They found that fingertip velocity during a keystroke was relatively constant, with the mean velocity of 45 mm/s for key travel of 3.5 mm taking 77.2 ms.

[5] This damping would dissipate the energy imparted to the key suspension (spring or rubber dome) and the energy associated with accelerating the key mass during key strike and return.

### 1.3. Scope

The long-term objective of this work is to investigate, characterize and quantify the mechanical impedance characteristics that contribute to the feel of computer keyboard keys. To accomplish this goal, a special-purpose test rig has been developed. The design of this test rig for the measurement of stiffness and damping characteristics of different computer keyboard keys is the subject of this paper.

## 2. DESIGN OF TEST RIG

### 2.1. Specifications

From the ISO/DIS 9241 standard for computer keyboard keys, the largest allowable value for key displacement is 6 mm of travel in one direction. To accommodate acceleration to constant velocity, the test rig has a stroke specification of 100 mm. As indicated earlier (footnote 4), the velocity required to simulate high speed typing (90 words/minute) is 60 mm/s. The velocity specification for the test rig was set at a maximum speed of 125 mm/s.

### 2.2. System Design

The test rig, shown in the drawing of Figure 2 and in the photograph of Figure 3, consists of a motorized positioning stage mounted to a brace which is attached to a bridge on a platform. The stage drives a probe that depresses the key to be tested; a load cell measures the applied key force. An optical incremental encoder measures the displacement of the stage-probe assembly and hence the key during key depression. The velocity of the key stroke motion is controlled by the motor speed and can be verified by differentiation of the key displacement-time history.

In conducting a test, a keyboard rests on the leveled platform. The platform (60 x 122 cm) was designed so any key on a multitude of keyboards can be tested with the probe in the center of the platform. The carriage of the positioning stage is driven up and down by a stepper motor. The carriage carries an arm with a load cell and probe head. The probe head is centered over the key strike surface to be tested and the probe travel is made parallel to the key stem vertical centerline.

By design, the force measurement and displacement measurement systems are integrated with the stage. Different keys on different keyboards can be tested quickly by simply interchanging keyboards on the platform without reconstruction of the test rig.

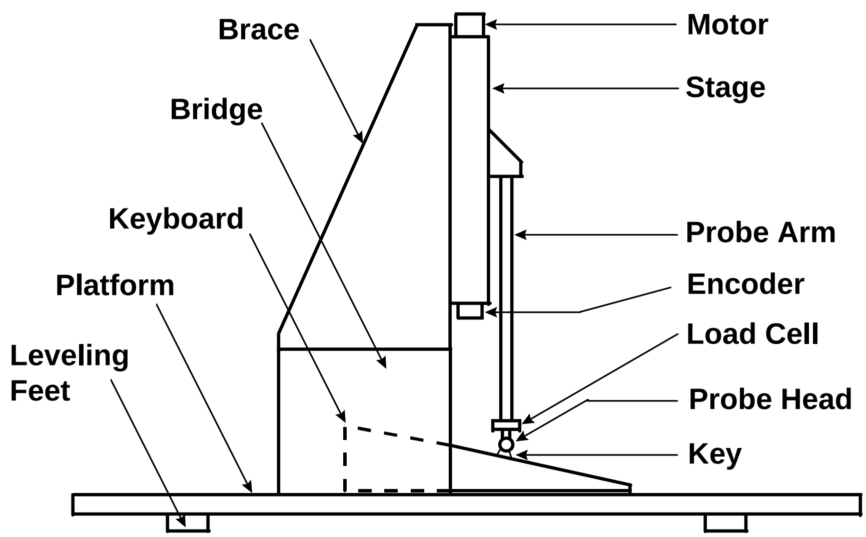


Figure 2. Side View of Test Rig

### 2.2.1. Force Measurement

A miniature-sized strain-gauge load cell (Sensotec, Inc., Model 31), which is mounted in-line with the probe, measures the contact force between the probe and the keycap. This load cell has two male-threaded rods on both surfaces for attachment to the probe head and arm. The load capacity of the cell is 1 $kg_f$ (9.81 N), which surpasses the maximum force subjects exerted on keys during typing (Gerard, 1997). The frequency response of the load cell is 1870 Hz, which is sufficiently high to capture high frequency force information during dynamic tests. A block diagram for the force measurement system is depicted in Figure 4.

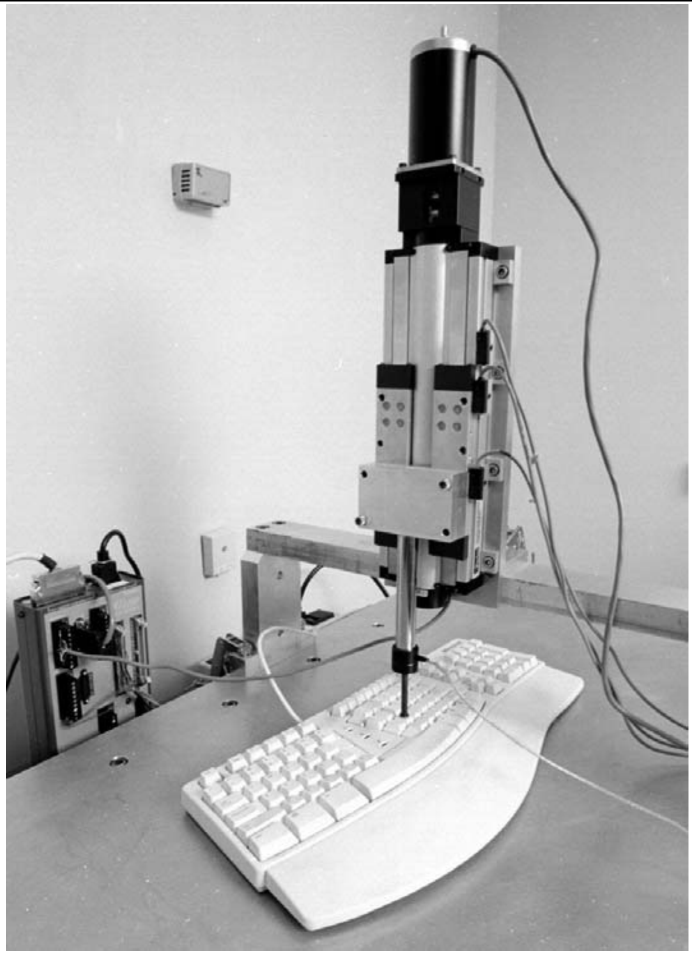

Figure 3. Photograph of Test Rig

Signal conditioning (by Sensotec, Inc., Model SA-4 case and SA-B card) involves supplying a 10 VDC excitation to the load cell and amplifying the cell's millivolt output signal to 0–5 VDC. A data acquisition (DAQ) system, consisting of a PC-bus (ISA based) board (National Instrument, AT-MIO-16E-10), is used to digitize the force signal. Since the board has 12 bit resolution, the smallest detectable force change (resolution) after digitization is 0.0024 N. The maximum throughput of the DAQ card is 100 kHz, and different sampling rates can be set by software.

### 2.2.2. Position Actuation and Measurement

The motion control and displacement measurement system is represented in the block diagram of Figure 5. Positioning is accomplished using a 5 mm-lead ground ball screw and square rail positioning stage (Daedal, Parker Hannifin Corp., model 404100XR). The stage converts rotational motion of an input shaft into translational motion of the carriage, enabling 100 mm of travel. A rotary optical

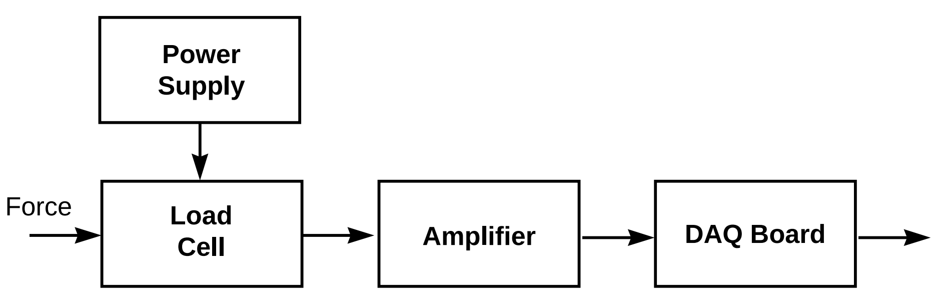


Figure 4. Force Measurement Block Diagram

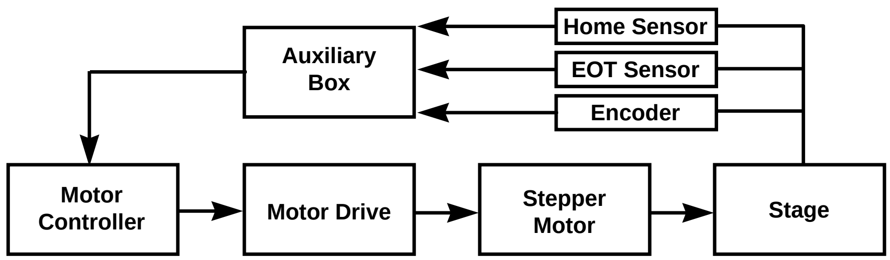


Figure 5. Motion Control and Displacement Measurement Block Diagram

encoder is attached to the lead screw of the stage. It measures the movement of the shaft, and thus indirectly the displacement of the carriage with a resolution of 1 μm. The stage includes three Hall effect sensors: a positive direction end-of-travel (EOT) sensor, a negative direction EOT sensor, and a home sensor.

The motor (Compumotor, Parker Hannifin Corp., model ZETA57-102) is a standard 200 full step hybrid motor, meaning the shaft of the motor turns 1.8° at one full step. A microstepping motor drive (Compumotor, Parker Hannifin Corp., model ZETA4) is used to divide a full motor step into micro-steps. The drive translates input signals of step pulses and direction signals into controlled current. The resolution of the drive is set at 25,000 steps per revolution. At the shaft speed of 0.1 rev/s (corresponding to the minimum test velocity of 0.5 mm/s), the step pulse frequency is 2500 Hz. At the shaft speed of 25 rev/s (corresponding to the maximum test velocity of 125 mm/s in dynamic measurement), the step pulse frequency is 625 kHz.

The step pulses are supplied by a ISA PC-bus motion controller card (Compumotor, Parker Hannifin Corp., model AT6200). A PC-bus based controller is employed, through which displacement information is sent to the PC from the encoder. External signals from the encoder, home sensor and EOT sensors are not fed directly to the controller card due to both electric isolation requirements and physical limitations. The signals from the encoder, home sensor and EOT sensors are wired to an auxiliary (AUX) box. The AUX box isolates external circuitry from the controller card, thus protecting the card from the hazards of voltage spikes and current surges. Information about the encoder and the sensors is then transmitted from the AUX box to the controller card through a high-density cable.

### 2.2.3. Data Flow and Processing

The integration of data acquisition (for force and position) and motion control is represented in the overall system block diagram of Figure 6. The motor controller card and DAQ board are installed in a Pentium PC running Windows 95 and LabVIEW (National Instruments). In the test system, DAQ drivers (National Instruments) operate the DAQ board (AT-MIO-16E-10), and a "Motion Toolbox" (Compumotor) is used to communicate with and command the motor controller card (AT6200). The Motion Toolbox is actually a library of LabVIEW virtual instruments (VIs).

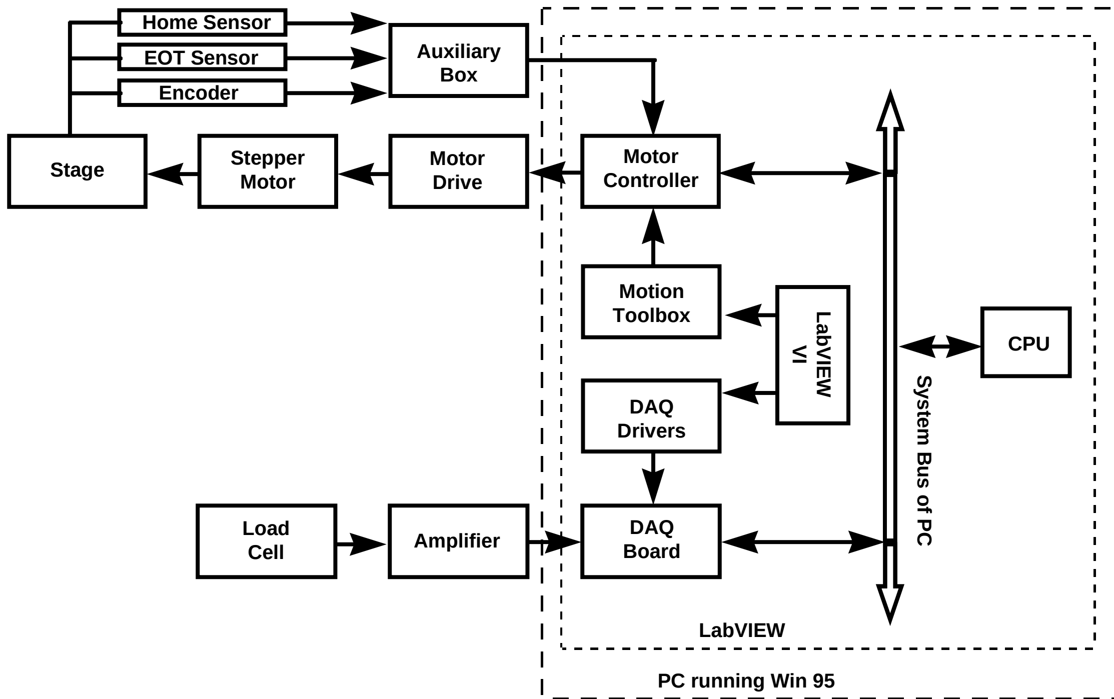


Figure 6. Test Device Actuation and Measurement Block Diagram

## 2.3. Control of Test Rig

The test rig can be used to conduct static and dynamic measurements to determine force-displacement and force-velocity characteristics, respectively. Static measurements are taken at 0.1 mm increments of travel.

In dynamic measurements, the probe is accelerated to a constant velocity ranging from 3 mm/s to 125 mm/s. At higher testing velocities, the sample rate is increased to capture the fast-changing force and displacement information. These measurements provide force, displacement, and velocity data for analysis and cross-plotting, and thus the ability to obtain the force-velocity characteristic of a key at any given travel position during its stroke. A flowchart of force, displacement, and velocity measurement is illustrated in Figure 7.

Prior to either static or dynamic testing, the probe head is moved to a user-defined reference position above the key to be tested. From the reference point, the probe initiates its travel depressing the key to its extreme bottom position. It then returns and stops at its reference point. The extreme bottom position is detected using the force signal as feedback. When the force exceeds a threshold value (set here at 7.0 N), the key is assumed fully depressed and the probe is commanded to move in the opposite direction.

Static and dynamic measurement testing procedures have been written, including user interfaces for control and measurement. An example of a LabVIEW VI is shown in Figure 8.

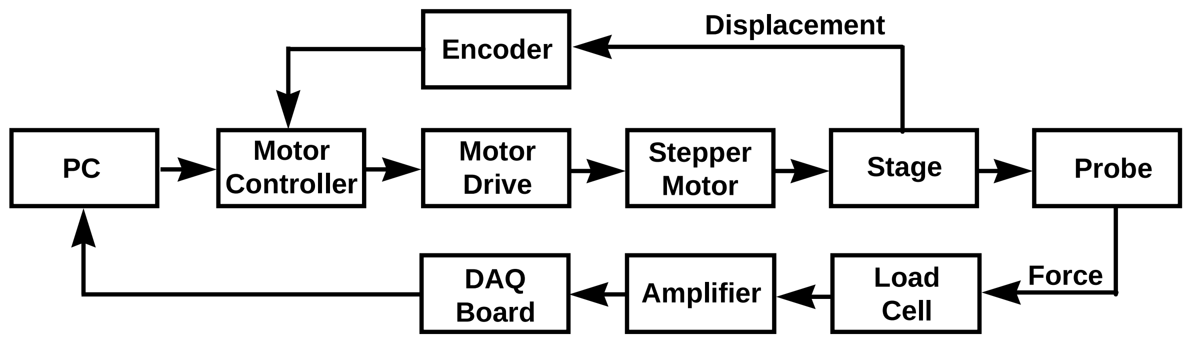


Figure 7. Feedback of Force and Displacement in Test Device

## 3. PRELIMINARY RESULTS

At the time of preparation of this paper, the test rig has been constructed and calibrated, and initial testing of keys has commenced. Figure 9 shows the force-displacement characteristic of a rubber-dome key being depressed and returned at a speed of 3.0 mm/s. The plot reflects the snap action that appears in the static ISO plot of Figure 1. The plot also shows hysteresis; the force is direction dependent in that the force is greater for key depression than for return. The energy dissipated in one cycle is represented by the area between the two curves.

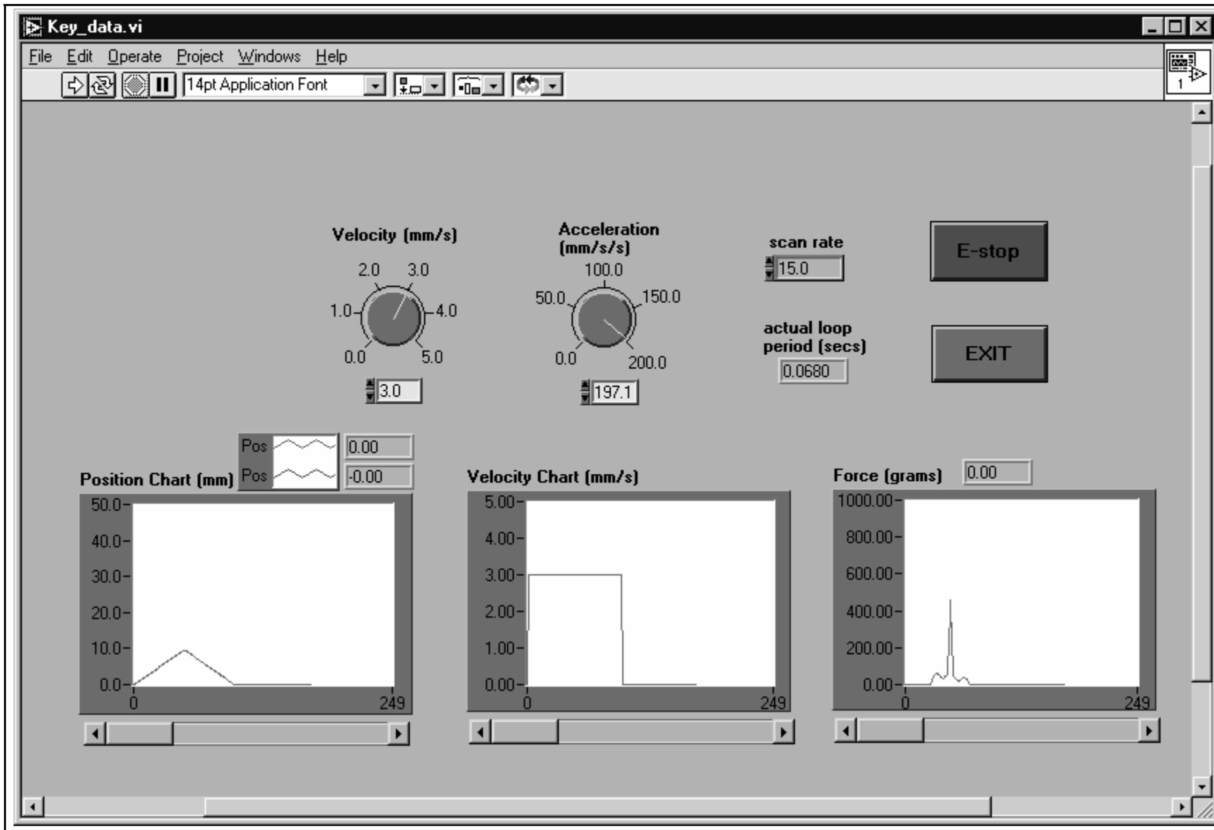


Figure 8. LabVIEW Control Panel During Testing

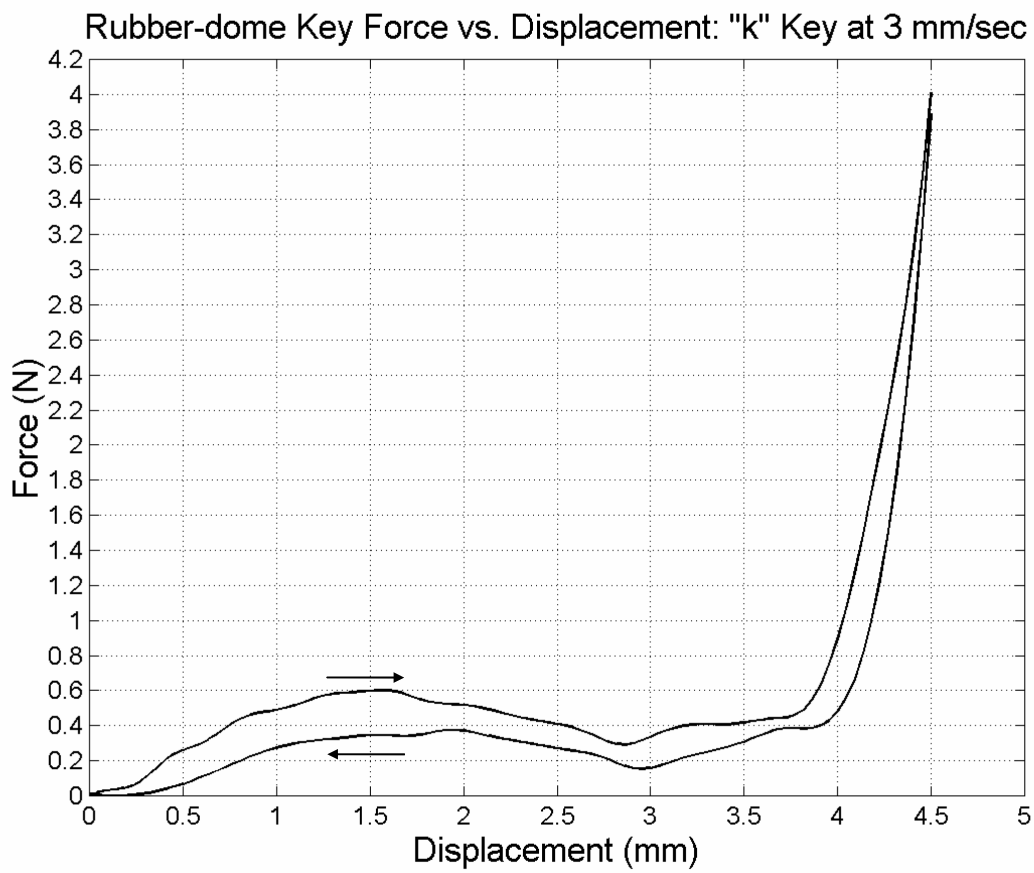


Figure 9. Force-Displacement Characteristic for Rubber-Done Key at 3.0 mm/s.

## 4. SUMMARY

This project addresses the characterization of mechanical stiffness and damping in spring-loaded and rubber-domed computer keyboard keys. These properties are ascertained by measurement of key force vs. key displacement and key force vs. key velocity characteristics, respectively, using a test-rig specifically designed for this purpose. The test rig is computer automated using PC-bus-based data acquisition and motion controller cards running under LabVIEW. The paper has focused on the development of this test rig, including its mechanical design and its associated computer control. Future work will be directed to extensive testing of keys, from which the mechanical impedance characteristics will be quantified.

A hypothesis of this work is that mechanical damping plays a perceptible and potentially significant role in the design of computer keyboard keys (important for the manufacturer) and in the selection of an "optimal" keyboard by a typist (consequential for the user). It is hoped that the quantification of both the static and dynamic mechanical properties of computer keyboard keys will lead to an enhanced understanding of ergonomic factors. Furthermore, this work could form the basis for a subsequent ISO standard for force-velocity characteristics of computer keyboard keys. Future research is also needed to investigate how damping of computer keys affects the etiology of WMSDs, such as carpal tunnel syndrome.

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