Proceedings of the American Control Conference
San Diego, California • June 1999

DESIGN OF A TEST RIG FOR MEASUREMENT OF STIFFNESS AND DAMPING CHARACTERISTICS OF COMPUTER KEYBOARD KEYS

Mark Nagurka, **Richard Marklin**, and **Kai Liu**
Department of Mechanical and Industrial Engineering
Marquette University
Milwaukee, WI 53201-1881

ABSTRACT

This paper describes the development of a special-purpose test rig for the measurement of stiffness and damping characteristics of computer keyboard keys. The ultimate 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 key displacement, velocity, and contact force has been designed. The objectives of the measurement and data analysis, and a description of the hardware and software configuration, including the data acquisition method and motion control system, are presented.

1. INTRODUCTION

The mechanical properties of computer keyboard keys are a result of their underlying mechanisms. Two general types of mechanisms – rubber-dome and coil-spring keys – exist to provide the necessary compliance and toggling action for a typist. 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 the shape of keyboards (Marklin et al, 1999; Simoneau, et al, 1999), key tactile feel remains an elusive and controversial topic. The tactile feel is elusive because our kinesthetic sense is a composite of several mechanical factors that are not easily isolated. In broad terms, the kinesthetic sense is the overall tactile *gestalt* of what we sense in interacting with the environment. Our inability to isolate mechanical properties of keys explains why we prefer some types of keys but cannot articulate our reasons well.

Depressing a key results in an overall tactile impression or feeling that can be quantified via 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 displacement rate of 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.

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

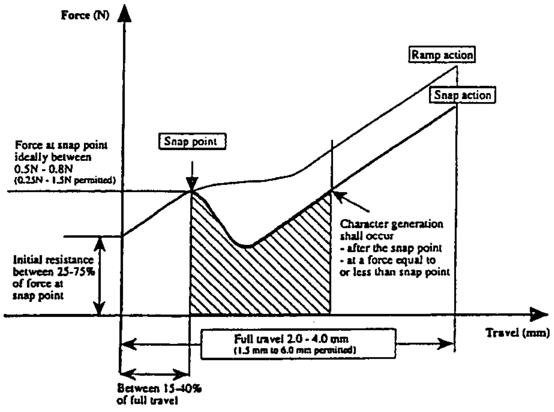

Figure 1. Relationship between key force and key displacement in ISO/DIS 9241/4.2 standard (ISO, 1995).

0-7803-4990-6/99 $10.00 © 1999 AACC

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.

The key force-displacement characteristic, specified in the ISO/DIS 9241 standard (ISO, 1995) and depicted in Figure 1, clearly indicates 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 between 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 electrical make point 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."

In practice, the "snap force" is also referred to as "peak force" or "actuation force" and is the value typically advertised by the manufacturer. The "make force" is the force value at the electrical closure of the switch as the key is depressed.

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 0.125 msec. This translates into a key velocity of 60 mm/sec for a key with 4 mm travel (in both depression and return and assuming a constant velocity)[1]. 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 10 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 (2x to 10x 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.

1.3 Scope

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

2. DESIGN OF TEST RIG

2.1 Specifications

The test rig must be capable of measuring three quantities: key force, key displacement and key velocity. Previous studies of human typists show that the maximum fingertip force applied during keying is 7.0 N (Rempel et al., 1994).

---

[1] 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 then being released. Assuming the time a key goes down is half of the above total time, the key down time is 6/W sec. The distance a key travels from its rest position to the bottom is S mm. As a result, the average velocity a key goes down is S×W/6 mm/sec. Assuming the largest possible value for W is 100 words per minute (reasonable for a fast typist) and the largest value for S is 6mm (the largest key displacement permitted by ISO), the maximum average velocity that a key goes down is 100 mm/sec. Assuming the lowest possible value of W and S are 30 words per minute and 2 mm respectively, the minimum average velocity that a key goes down is 10 mm/sec. These calculations agree with the results found by Rempel et al. (1994) in research on human fingertip keying. They found that the fingertip velocity during keystroke is relatively constant. The mean velocity for a group of subjects was 45 mm/sec with the distance of key travel of 3.5 mm and the average duration of keystroke of 77.2 msec.

This value, which is significantly larger than the force necessary for depression to full travel (see Figure 1), was used as an upper bound in selection of an appropriate force sensor. To establish the frequency response requirement for the force sensor, a Discrete Fourier Transform (DFT) was performed of key force data from Rempel et al. (1994). From the DFT, the highest frequency component in human keying force was found to be 100 Hz. To avoid filtering out possibly useful high frequency components in the dynamic measurements, it was decided to specify a force sensor with a frequency response greater than 100 Hz.

From the ISO standard, 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 1), the velocity required to simulate high speed typing (100 words/minute) is 100 mm/sec. The velocity specification for the test rig was set at 25% greater than the maximum speed (125 mm/sec).

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 to enable testing of any key on a multitude of keyboards 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 attached to which is 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.

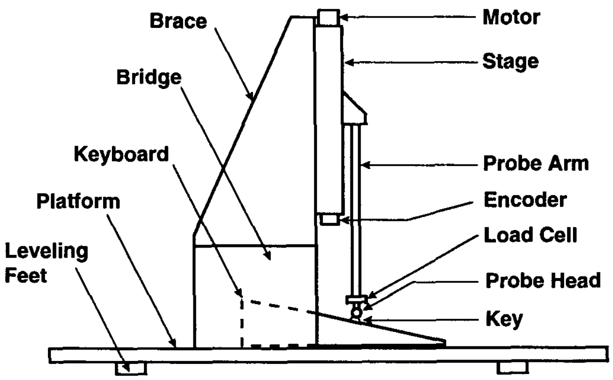

Figure 2. Side View of Test Rig

2.2.1 Force Measurement

A miniature-sized strain-gauge load cell (Sensotec, Inc., Model 31) is mounted in-line with the probe to measure the contact force between the probe and the keycap. The load capacity of the cell is 1 kg (9.81 N), which surpasses the force specification of 7.0 N. The frequency response of the load cell is 1870 Hz, which is sufficiently high to capture high frequency force information during dynamic tests.

The force measurement requires signal conditioning (achieved via Sensotec, Inc., Model SA-4 case and SA-B card) to supply 10 VDC excitation to the load cell and amplify the load cell output signal to 0–5 VDC. A data acquisition (DAQ) system, consisting of an ISA PC 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 0.0024N. 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

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 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 that 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/sec (corresponding to the minimum test velocity of 0.5 mm/sec), the step pulse frequency is 2500 Hz. At the shaft speed of 25 rev/sec (corresponding to the maximum test velocity of 125 mm/sec 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). Since intensive communications and data processing between the PC and controller are required, a PC-bus based controller (rather than a slower series or parallel communication method) is employed. Through the controller, 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 first 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 force and position data acquisition and motion control is represented in the overall system block diagram of Figure 4. The motor controller card and DAQ board are installed in a Pentium 90 MHz IBM 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).

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 actually quasi-static, since the probe depresses the key with a velocity of 0.5 mm/sec. Since the desired smallest resolution is 0.01 mm, the sample rate is set to 50 Hz (0.5 mm/sec divided by 0.01 mm).

In dynamic measurements, the probe strikes the key at constant velocities ranging from 10 mm/sec to 125 mm/sec. 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.

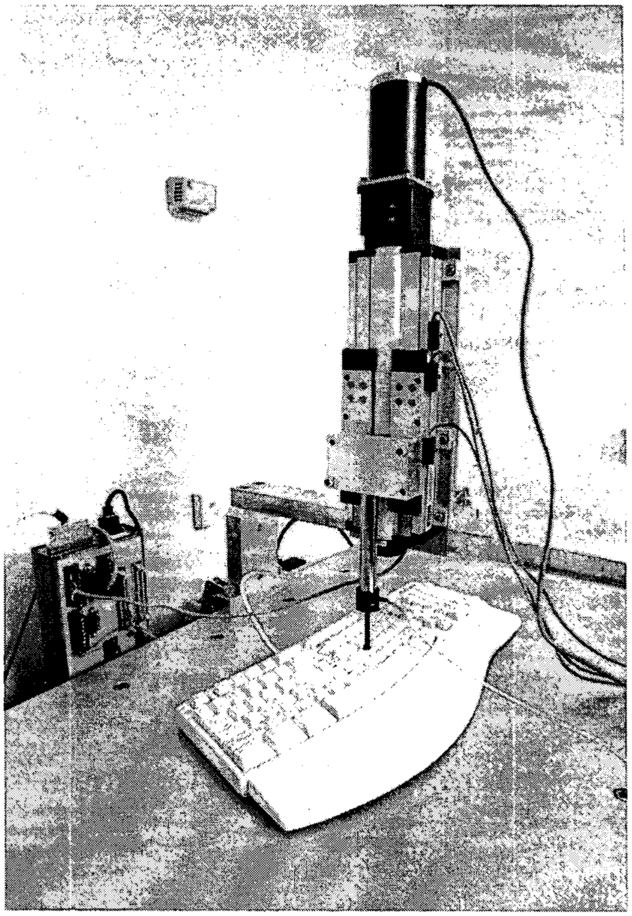

Figure 3. Photograph of Test Rig

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 5.

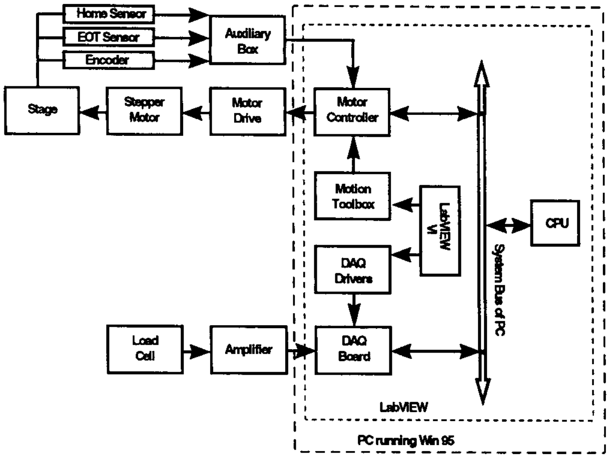

Figure 4. Actuation and measurement block diagram

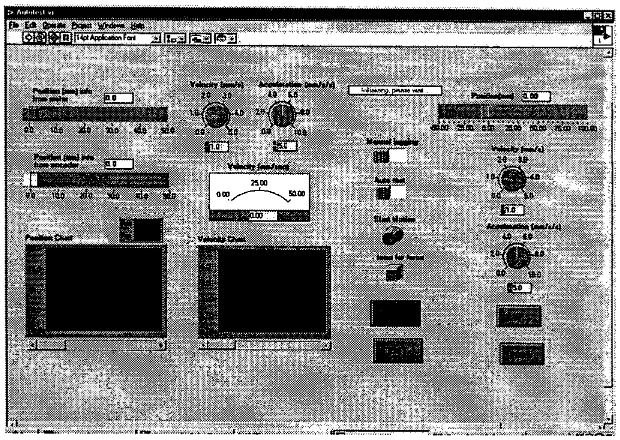

Figure 5. LabVIEW Display for control and data

3. CLOSING

The damping characteristics of computer keyboard keys are not known and could play a role in the etiology of WMSDs related to typing activity. Certainly, some damping is desirable to dampen unwanted oscillations of the key. Significant damping would not be desirable, since it would make the key force high during fast keystrokes. However, there may be a range of damping that offers optimal tactile feedback to a typist.

This project addresses the characterization of mechanical stiffness and damping in spring-loaded and rubber-domed computer keyboard keys. These properties are to be 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. This paper has focused on the development of the 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.

4. ACKNOWLEDGEMENT

The authors wish to thank Mr. Jim Whitaker (Department of Mechanical and Industrial Engineering, Marquette University) for his expertise in fabricating the test rig prototype. The authors also wish to acknowledge the assistance of Mr. Bill Scallon (Braas Corp.) for his technical suggestions in selecting actuator and sensor components.

5. REFERENCES

Armstrong, T., Foulke, J., Martin, B., Gerson, J., and Rempel, D., 1994, "Investigation of Applied Forces in Alphanumeric Keyboard Work," American Industrial Hygiene Association, Vol. 55, No. 1, January, pp.30-35.

Gerard, M.J., 1997, "The Effects of Keyboard Stiffness on Typing Force, Finger EMG, and Subjective Discomfort," Doctoral Dissertation, University of Michigan, Ann Arbor, MI.

ISO, 1995, Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs), Part 4: Keyboard Requirements of Standard ISO/DIS 9241-4.2.

Kroemer, K.H.E., 1972, "Human Engineering the Keyboard," Human Factors, Vol. 14, No. 1, pp.51-63.

Marklin, R.W., Simoneau, G.G., and Monroe, J.F., 1999, "Wrist and Forearm Postures From Typing on Split and Vertically-Inclined Computer Keyboards," Human Factors, *submitted.*

Rempel, D., Dennerlein, J., Mote, C., Armstrong, T., 1994, "A Method of Measuring Fingertip Loading During Keyboard Use," J. Biomechanics, Vol. 27, No. 8, pp.1101-1104.

Simoneau, G.G., Marklin, R.W., and Monroe, J.F., 1999, "Wrist and Forearm Postures of Users of Conventional Computer Keyboards," Human Factors, *in press.*