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Thresholds for Dynamic Changes in a Rotary Switch

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Abstract. Switches are everyday objects that interface humans to many functionalities and influence our perception of the machinery that they are attached to. This study is aimed at a better understanding of the perceptual attributes of switches. Specifically, the perceptual thresholds for dynamic changes in a rotary switch were evaluated in two experiments using an adaptive procedure. Exp. I measured human's ability to detect the presence of a random noise superimposed on a sinusoidal torque vs. angular position profile. The detection thresholds were found to be in the range 1–3% of the peak torque. This high sensitivity was interpreted as being consistent with the existing literature in that humans are more sensitive to stimulation at high frequencies than that at low frequencies. Having established the importance of switch dynamics in its perception, Exp. II measured detection thresholds for sinusoidal torque variations with spatial frequencies ranging from 2.8° to 180°. Average thresholds varied from 0.37 to 26.17% of the average torque (30 N·mm) over the aforementioned spatial frequency range. These experiments provide quantitative results on our ability to detect dynamic events in a rotary switch. They shed new insight on the design and specification of rotary switches.

1 Introduction

This study focuses on a group of common haptic objects known as switches. Switches come in many shapes and forms in our everyday life. They not only serve important functions but also color our daily experience. The way a headlight switch looks, feels and sounds inside an automobile, for example, influences our perception of not only the quality of the switch but the car as well. What then, are the perceptual attributes of switches? What makes one switch feel different from another? What engineering metrics help to predict the haptic percept of a switch? How can a target percept for a switch be translated into engineering design specifications for mass production?

Many studies have investigated the feel of switches, and ways of emulating switches with electromechanical devices. One of the earliest studies on torque sensitivity was conducted by Woodruff and Helson [1]. Using a steel rod mounted on two ball-bearing assemblies, they measured Weber fractions for torque discrimination using different knob sizes and varying weights suspended from the rod. MacLean proposed the idea of using a haptic interface to capture the force-distance characteristics of a switch (e.g., a toggle switch), and use the same haptic device to emulate the switch [2, 3]. An instrumented haptic object was used as an expressive media for multimodal communication [4] and for manipulating digital media [5]. Recently, Hasser and Cutkosky modeled the dynamics of human hands holding a haptic knob in a simple pinch grasp with a second-order system [6]. Such a model can lead to better algorithms for the stable control of an active switch. Realizing the importance of haptic interfaces in an automobile, car manufacturers have embraced the idea of a control dial with active haptic feedback. Examples include the iDrive system co-developed by Immersion Corporation and BMW, and the Haptic Scroll Wheel in a Nissan concept car. Despite all these efforts, much work still remains to fully understand the perceptual attributes of a switch.

Our work is motivated by the desire to find a parsimonious set of engineering parameters that uniquely determines the percept of a switch. Traditionally, switch performance has been characterized by torque vs. travel (angular position) profiles for rotary switches. Manufacturers of switches are often given such profiles with fixed, say 10-30%, tolerance. We argue that these profiles are not sufficient to describe the perception of the resultant switches. We show that the dynamic behavior of a switch plays an important role in the way a switch feels to the fingers. Two experiments are reported in this paper. In the first experiment, we demonstrate the extraordinary sensitivity of human fingers to the high-frequency noise in switch dynamics. In the second experiment, we characterize the thresholds for switch dynamics as a function of spatial frequency.

2 Experiment I: Torque Profile Roughness Threshold

Informal observations indicated that humans are extremely sensitive to minute "buzzing" noise during an otherwise smooth turn of a rotary switch. To quantify this perceptual phenomenon, we investigated the detection thresholds for random variations in the torque profile of a rotary switch.

2.1 Method

The experimental apparatus consisted of a rotary motor (Maxon RE25 118752), an optical encoder (Computer Optical Product, CP950), a power amplifier (Trust Automation 115), and a transformer (CUI MPS100-24). As shown in Fig. 1, a rotary knob is attached to the end of the motor shaft. The subject grasped the knob with the thumb and the index finger of the left hand, and turned the switch to the left (i.e., counter-clockwise). The torque resisting the turn was programmed to follow a chosen profile as a function of angular position.

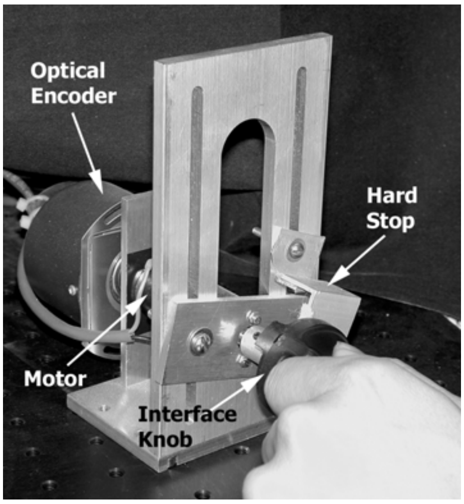
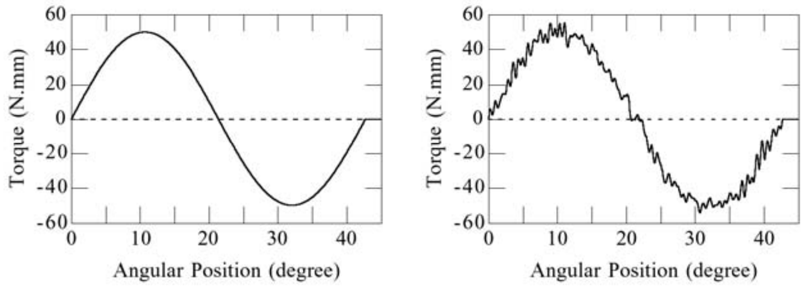


Fig. 1. Experimental apparatus used in both Exp. I and II. A rotary motor applied the torque profile for a stimulated rotary switch. Subject grasped a rotary knob that interfaced the thumb and the index finger to the motor shaft

The stimuli used in Exp. I were characterized by the typical sinusoidal torque vs. angle profiles for a rotary switch (Fig. 2a). Fig. 2b shows a low-frequency sinusoidal profile superimposed with a white noise signal. Each noise sample was generated from a uniform distribution centered at 0 peak-torque level. The signal was then filtered in the spatial domain by a 4^{th}-order Butterworth low-pass filter with a cutoff frequency that was 32 times that of the original low-frequency signal. The subject's task was to detect the presence of the noise, or equivalently, to discriminate between a "smooth" turn (Fig. 2a) and a "rough" turn (Fig. 2b).

Nine subjects (3 females and 6 males) participated in Exp. I. The subject sat in front of a table with the apparatus on the left and a computer monitor and a keyboard on the right. During the experiments, the subject was instructed to rest the left elbow on the table in a comfortable position. A black cloth was placed between the apparatus and the keyboard to prevent the subject from seeing the hand or the apparatus. A noise-reduction earphone was worn by the subject to eliminate any possible auditory cues emanating from the apparatus.

A brief training procedure was conducted at the beginning of each run. After entering the experimental parameters for the run, the subject was given an opportunity to feel either stimulus alternative by clicking on the corresponding button. The training was self paced and lasted as long as the subject wished. Data collection began when the subject terminated the training.



(a) (b)

Fig. 2. Stimuli used in Exp. I. Subject felt either a smooth sinusoidal torque profile (Fig. 2a) or one superimposed with random noise (Fig. 2b). Magnitude of the superimposed noise varied from trial to trial depending on the subject's response to the previous trial

A one-up two-down adaptive procedure was employed to estimate the threshold corresponding to the 70.7% level on the psychometric function [7]. On each trial, the subject felt, in random order, the two rotary switches shown in Fig. 2. The subject's task was to indicate which switch felt "rougher". The noise level (defined by the width of the random noise distribution) increased after each incorrect response ("one-up") and decreased after two consecutive correct responses ("two-down"). The noise level at which stimulus intensity changed from increasing to decreasing (or vice versa) was called a "reversal." The average value of the noise levels from the last 3 reversals was recorded as the estimated threshold.

2.2 Results

Thresholds ranged 0.5 to 1.5 N·mm for a peak torque value of 50 N·mm. The data correspond to a noise sensitivity of 1 to 3% of the peak torque. These values are considerably lower than the force thresholds (Weber fraction) of 5-10% reported in the literature [8] [9], or the torque threshold of 4-12% [1]. This is mainly due to the difference in the way stimuli were generated. Most studies on force or torque discrimination threshold require the subject to discriminate between two constant or slowly-varying force profiles. An equivalent construction would be to have a subject discriminate between the profile shown in Fig. 2a and a similar sinusoidal profile with a larger amplitude. The pair of stimuli we used in Exp. I differ in the *high-frequency* noise component. Therefore, our results are *detection* thresholds for high-frequency noises, rather than discrimination thresholds. The fact that our thresholds are much lower than reported force/torque discrimination thresholds is consistent with the general knowledge that the somatosensory system is more sensitive to high frequency vibrations (especially in the range 200-300 Hz, mediated by Pacinian corpuscles) than to low frequency motions [10].

3 Experiment II: Detection of Spatial Torque Variations

The results of Exp. I indicated that humans are extremely sensitive to high-frequency dynamic behavior of a switch. Exp. II was designed to investigate this sensitivity further by measuring the detection thresholds for spatial torque variations at seven spatial frequencies over a 64-fold range.

3.1 Method

The same experimental apparatus shown in Fig. 1 was used in Exp. II. Five subjects (1 female and 4 males) participated in these experiments. The stimuli consisted of either a constant torque or one superimposed with a sinusoidal torque variation (Fig. 3). Visual and auditory shields were used throughout the experiments to eliminate possible extraneous cues.

Before each run, the subject could feel either the constant or the sinusoidal torque profile for as many times as they wished. Data collection began after the subject terminated the training. A three-interval forced-choice paradigm combined with a one-up three-down adaptive procedure was employed because it has been shown to be most efficient by a number of investigators (see [11] for a review). On each trial, the subject turned the rotary knob three times ("three intervals"). A mechanical hard stop was used to ensure that each turn started from the same position, and a small torque in the clockwise direction kept the knob at the hard stop when the subject was not applying any force to the knob (see Fig. 1). As the subject turned the switch in a counter-clockwise direction, resistive torque in the clockwise direction was applied to the knob according to the torque vs. angle profile such as the one shown in Fig. 4. The total travel was limited to 90°. At the end of the travel, applied torque dropped to zero. As the subject brought the knob back to its resting position, a small restoring torque was applied to help bring the knob to the mechanical stop. This completed one turn. Of the three turns the subject had to execute for each trial, two of them (randomly selected) contained a constant torque profile, and the remaining turn contained a sinusoidally-varying torque profile. The subject's task was to indicate which of the three intervals contained the sinusoidal profile. The response was then used by the adaptive procedure to determine the amplitude of the sinusoidal signal for the next trial. No feedback was provided. Amplitudes were changed initially by 4 dB and then by 1 dB after the first three reversals. An experimental run was terminated after 12 reversals at the 1-dB step size. Each run typically lasted 70-90 trials. The threshold was estimated as the average of those last 12 reversal amplitudes. Detection thresholds obtained this way correspond to 79.4% correct responses [7]. To estimate the standard error of the estimate of the threshold, 6 estimates of the threshold were calculated from the 6 pairs of the 12 reversals, and the corresponding standard error was obtained (see [12] for a description of a similar experimental procedure and data analysis technique).

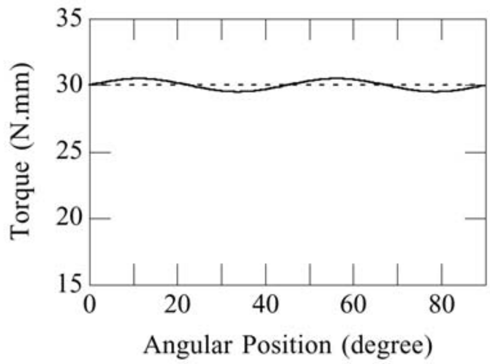


Fig. 3. Torque profiles used in Exp. II, shown with a spatial period of 45°. Offset torque was kept at 30 N·mm. Subject either felt a constant torque (*dashed line*) or a variable torque (*solid line*) as a function of angular position. Amplitude of the superimposed sinusoidal signal varied from trial to trial depending on the subject's response to the previous trial. Spatial period varied from run to run

3.2 Results

Thresholds obtained from the five subjects are shown in Fig. 4. For each subject, thresholds increased as the spatial period of the sinusoidal variation increased. Thresholds averaged over the five subjects varied from 0.11 to 7.85 N·mm, corresponding to 0.37 to 26.17% of the average torque value. This represents a 71-fold increase in threshold over a 64-fold increase in the spatial frequencies of the torque variations. This trend indicates an almost linear growth of threshold as a function of spatial period. It shows that it is much easier for humans to detect a fast-varying dynamic behavior in the switch than to detect a slowly-varying one.

Subject SY and PB's data are quite similar (p=0.9894) and appear to be the lowest in Fig. 4. These two subjects have had the most experience with the rotary switch emulation apparatus from debugging experimental procedures, and from participating in other psychophysical experiments involving the same apparatus. A Tukey's HSD procedure revealed three groups of subjects: (1) SY, PB and HT, (2) SC, and (3) ZP, with increasing detection thresholds [critical value q(0.32148; 175) = 3.89818, minimum significant difference = 0.341]. The mean thresholds for subjects SY, PB, HT, SC and ZP were 1.5303, 1.5314, 1.7334, 3.1189 and 3.9316, respectively.

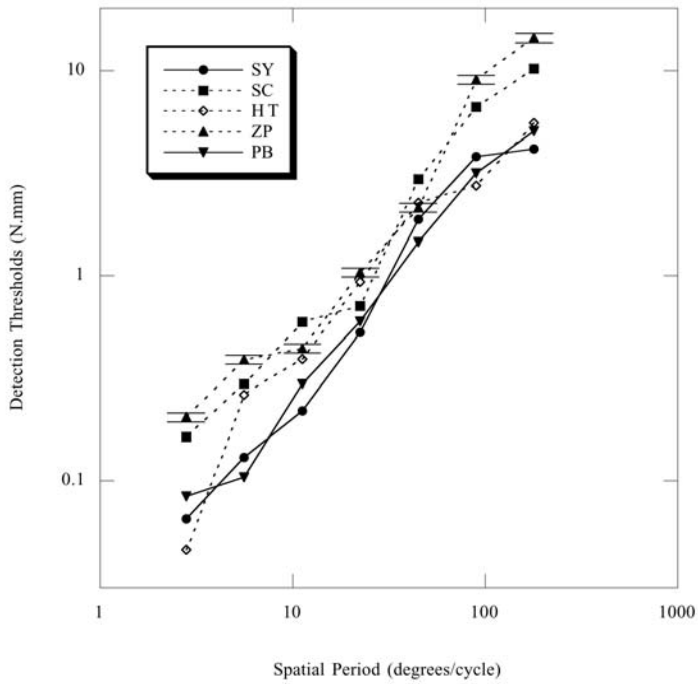


Fig. 4. Detection thresholds for sinusoidal torque variations for all five subjects. Data from each subject are plotted with the same symbol. Threshold is plotted as the amplitude of the sinusoidal torque variation (see Fig. 3) against the spatial period of the same. For clarity, only the ±1 standard error bars for subject ZP are shown. These error bars are representative of other subjects' data. Solid lines are used for subject SY and PB whose thresholds are significantly lower than those of the other subjects'

4 Discussion

Several factors might have affected the detection thresholds obtained in Exp. II. First, there is the question of whether detection thresholds depended on the speed with which a subject turned the rotary knob. One alternative interpretation of the results in Fig. 4 would be that thresholds increased as *temporal* frequency decreased. We define temporal frequency as the ratio of rotating velocity (degree/sec) over spatial period (degree/cycle). Some subjects commented on the impression of an "optimal" velocity with which they performed the best. It would therefore be interesting to investigate the relationship between detection threshold and temporal frequency. Such results can be directly compared to similar data in literature where stimuli are characterized in position but not force or torque (e.g., [10]). Second, there is also the question of whether detection thresholds depended on the average torque value. According to [1], torque discrimination threshold decreased from 12.6 to 4.4% when the reference torque increased from 8.35 to 100 e-gm (equivalent gram-meter). It is therefore necessary to investigate whether the thresholds obtained in Exp. II would change if the average torque was different. These issues will be topics for future studies.

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