ORIGINAL ARTICLES

BOWSTRING EVALUATION BASED ON *Kansei* ENGINEERING TECHNOLOGY

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Abstract: The purpose of this study is to assess bowstrings of different materials based on the measurement of dynamic factors such as the archer's "feel," bow vibration, arrow speed, etc. Shooting experiments and questionnaire have been conducted with subjects using 4 types of bowstrings of different materials. Results suggest that hemp bowstrings have the highest logarithmic decrements in bending and twisting vibration and showed that differences in bowstring material have little effect on vibration frequency. The energy transmission efficiency of a Japanese bow with bowstrings of Kevlar, Technora, and Vectran, was about 69%, compared to 67.7% for a hemp bowstring. We found a relationship between results of the χ^2 test in questionnaires and measured values, suggesting that KANSEI Engineering technology in evaluation based on the measurement of dynamic factors related to arrow release is effective in improving bowstring evaluation and "feel" in use.

Keywords: *Bowstring, Japanese-style bow, vibration, energy transmission efficiency, Kansei Engineering Technology*

1. FOREWARD

Until 30 years ago, Japanese bows were made of wood and bamboo, then bowstrings were made of hemp. From the late 1960s, newly developed fibers were applied to personal-use products and sporting goods. The current mainstream materials for Japanese bows are glass or carbon fiber, and most arrow shafts are aluminum or duralumin. Bowstrings of chemical fibers such as Kevlar are cheaper than hemp and highly popular.

Japanese bowstrings are conventionally judged acceptable only if they remain unbroken, but archers using them attach importance to such bowstrings. In Japanese archery matches, for example, they use moderately used bowstrings rather than new or overused ones. New bowstrings are highly expandable, changing the shape of the Japanese bow when they expand and thus influencing the arrow's destination. Archers gain this knowledge through experience. Overused bowstrings may snap in competition and their "feel" after release is poor due to overstretching, which means they are often replaced by new strings before breaking.

Although the modulus of elasticity and the strength of the fiber material used for bowstrings are clearly defined[1], bowstring features as a product may change. If bowstring material is changed, an archer's shooting may be affected. As stated, archers sensitive to the difference in "feel" are likely to feel a difference when bowstring material is changed.

We therefore assessed bowstrings of different materials based on the measurement of dynamic factors such as the archer's "feel" in shooting, bow vibration, and arrow speed. Clarifying the relationship between dynamic factors measured and an archer's "feel" could help develop bowstrings and related sporting goods with a better "feel."

2. METHODS

2.1. Test specimens -- bowstrings, bows, and arrows -- and subjects

Bowstrings in experiments used 4 types of material -- aramid fiber Kevlar (A) and Technora (B), polyester fiber Vectran (C), and hemp (D) (Table 1). Bowstrings

Table 1 Test Bowstring

Bowstring	A	B	C	D
Material	Aramid Fiber	Aramid Fiber	Polyester Fiber	Hemp
Trademark	Kevlar	Technora	Vectran	-
Mass (g)	7.5	6.5	5.5	8.5

were shot about 20 times before experiments to expand them. Note that mass values were measured using bows with energizing tape as an electrode to detect release time.

Experiment used bow of glass fiber having nearly the same strength as those usually used by subjects during training. Bows were regarded as linear springs within the bow drawing distances of 0 - 0.8 m. The test bow's spring constant was 198.6 N/m. The arrow had a shaft of duralmin 0.96 m long and 0.026 kg mass.

Subjects in shooting experiments were 8 grade-holding experienced men and 2 women from a university Japanese archery club.

2.2. Testing

Each subject conducted 5 shooting tests each for 20 times per subject using straw targets in an experiment room (Fig. 1). The initial distance from the bowstring to the grip was set at 0.15 m for each subject and shooting trial.

Figure 1: Experiment

Bending and twisting vibration were measured using strain gauges on the front and back of the bow near the grip. Signal issued at release was detected using a makeshift switch circuit with energizing tape attached to the bowstring and the right hand grip holding the bowstring. Arrow speed just after release was calculated from induced electromotive force signals issued from a small ceramic magnet inside the arrow shaft passed through 2 hollow coils. Note that the

sampling time for analog-to-digital (A/D) signal conversion was set at 0.1 ms. Questionnaires solicited free comment by archers on release "feel" after each trial.

2.3. Calculation of logarithmic decrements of vibration and frequency analysis

Bow bending vibration after release is shown in Fig. 2. To determine how differences in bowstring material affected bow vibration, we measured the logarithmic vibration decrement for each trial. Ideal damped vibration is generally determined from the ratio of adjacent maximum values. Instead, we drew an approximate curve based on each maximum and, from resulting formulas, obtained logarithmic decrements of bending and twisting vibration. Bending and twisting vibration frequencies were analyzed using fast Fourier transforms (FFT).

Figure 2: Calculation of logarithmic decrement calculation curve approximation

2.4. Energy transmission efficiency calculation

The same bows were provided to each subject. The full bow draw differs between subjects or shooting trials by the same subject, preventing the effect of

difference between bow material from being determined from initial arrow speed just after release. We attempted to compare the effect of differences in bowstring material by calculating the energy transmission efficiency from the potential energy of a fully drawn bow to the dynamic arrow energy as shown by the formulas below. Displacement in formulas was measured using a strain gauge for measuring bending vibration. Displacement was converted from strain just before release, with the relationship between displacement and strain calibrated beforehand.

$$\text{Energy Transmission Efficiency (\%)} = \frac{KE}{PE} \times 100$$

$$KE = \frac{1}{2} m v^2$$

m: Arrow mass
v: Arrow speed

$$PE = \frac{1}{2} k x^2$$

k: Bow spring constant
x: Bow displacement

2.5. Questionnaire data processing

For questionnaires on “feel” at release, χ^2 was assessed for data classified and summed for several items to determine significant deviations, if any, between answers due to differences in bowstring material.

Figure 3: Logarithmic decrement of bending vibration

3. RESULTS AND DISCUSSION

3.1. Effects of vibration on logarithmic decrement

The logarithmic decrement (mean $\pm$ S.D., data n=50) of bending vibration in bowstring use (Fig.3) showed that the decrement is higher in the order of Kevlar (A) (0.61 ± 0.01), Technora (B) (0.64 ± 0.13), Vectran (C) (0.65 ± 0.14), and hemp (D) (0.70 ± 0.11). The difference between paired means for the logarithmic decrement of bending vibration was assessed (*t* test: 2-tailed test). The difference between means for the paired Technora (B) and Vectran (C) was insignificant, but that between means for all other pairs was statistically significant.

The logarithmic decrement of twisting vibration (mean $\pm$ S.D., data n=50) (Fig. 4) showed that the decrement is successively higher in the order of Technora (B) (0.32 ± 0.06), Kevlar (A) (0.35 ± 0.08), Vectran (C) (0.42 ± 0.07), and hemp (D) (0.51 ± 0.06). The difference between means for the logarithmic decrement of twisting vibration pairs (*t* test: 2-tailed test), was not statistically significant for Kevlar (A) and Technora (B) but was between all other pairs.

The decrements of bending and twisting vibration in hemp bowstrings (D) were relatively high. Kevlar (A), Technora (B), and Vectran (C) showed numerical values nearly the same for strength, elastic modulus, etc.[1], but significant differences were seen between logarithmic decrements of vibration, suggesting possible

Figure 4: Logarithmic decrement of twisting vibration

influence of bowstring strength and modulus of elasticity as a product, and such factors must be measured in future.

In results for bending and twisting vibration frequency analysis for each bowstring, based on FFT (Figs. 5 and 6), note that output from the strain gauge used to sense bow bending was calibrated for the distance [m] of the bow drawn and output of another strain gauge used to sense bow twist to torque [N·m] acting on the grip is represented by power spectra after subjecting them to frequency analysis for 200 ms after

release. For all subjects and trials, power spectra gave nearly the same results, clarifying differences between bow materials on frequencies of vibrations was negligible.

3.2. Effect on energy transmission efficiency

Figure 7 shows energy transmission efficiency (mean $\pm$ S.D., data n=50) for each bowstring. Kevlar (A) ($69.0 \pm 3.3\%$), Technora (B) ($69.1 \pm 3.5\%$), and Vectran (C) ($69.4 \pm 3.4\%$) were nearly the same notwithstanding different bowstring mass. The hemp (D) bowstring yielded a rather lower $67.7 \pm 3.9\%$.

Figure 5: Power spectra for bending vibration

Figure 6: Power spectra for twisting vibration

From the results of tests (t test: 2-tailed test) on the difference between means of energy transmission efficiency of paired bowstrings, a significant difference was seen between means for pairs of 3 bowstrings -- Kevlar (A), Technora (B), and Vectan (C) -- and that of hemp (D). Measurement of high-speed images, etc., showed that an arrow and bowstring separate when the bowstring is stretched straight (initial bowstring span) when the bow returns from its fully drawn state[2]. When the bowstring is stretched straight, maximum tension is imposed on the bowstring. The viscoelasticity of a bowstring as a product observed when a large force is applied in a short period thus may affect the speed of the released arrow.

Figure 7: Energy transmission efficiency on bowstrings

3.3. Correspondence of questionnaire results to dynamic factors

Answers by subjects on “feel” and impressions

were classified into 4 -- (1) vibrations and impact, (2) bowstring sound, (3) rate of bowstring recovery, and (4) others (Table 2). For the Kevlar (A) bowstring routinely used by 8 of the 10 subjects, “Feel” as usual and “No extraordinary impression” were in the majority, so the Kevlar (A) bowstring was excluded from analysis in subsequent procedures. Answers were thus analyzed based on Technora (B), Vectran (C), and hemp (D) for the 4 items above.

If bowstring material does not affect “feel” in release, the number of answers to each item given by subjects approaches the expected frequency calculated from total answers to items in parentheses. The χ^2 test was used to determine the adaptability of the expected frequency to the number of answers for each item. The statistical test quantity gave $\chi^2(6) = 12.69 > 12.59$ ($p < 0.05$, Table 3), suggesting that deviations in the number of answers are significant. Residual variance analysis was done to determine which cell in Table 2 contributed to this significance (Table 4).

Bowstring sound for the Vectran (C) bowstring and vibration/impact for the hemp (D) bowstring contributed to the significance of deviations in the number of answers. Accordingly, for the Vectran (C) bowstring, the fact that the number of answers on bowstring sound was fewer than the expected frequency suggests that bowstring sound does not affect “feel.” For the hemp (D) bowstring, the fact that the number of answers on vibration/impact exceeded the expected frequency and their content suggest that vibrations/impact highly affect “feel.” The hemp (D) bowstring showed a notably large difference from other bowstrings in logarithmic decrements of bending and twisting vibration and energy transmission efficiency, indicating that these dynamic factors influence the archer’s “feel” a great deal.

Table 2 Summarized questionnaire results

Test bowstring Answers	B	C	D	Number of answers
(1) Vibrations and impact	12(17.3)	16(17.6)	27(20.1)	55
(2) Bowstring sound	11(7.2)	3(7.4)	9(8.4)	23
(3) Rate of bowstring recovery	15(14.7)	20(15.1)	12(17.2)	47
(4) Others	10(8.8)	10(9.0)	8(10.2)	28
Number of answers	48	49	56	153

Number of answers (expected frequency)

As stated earlier, we found a correspondence between logarithmic decrements of vibration, energy transmission efficiency, etc., on the archer's sensitivity, indicating KANSEI Engineering technology evaluation based on measurement of dynamic factors related to release is effective when improvements are attempted to assess the bowstring as a product or to enhance "feel."

Table 3: Chi-Square Distribution (df = 6)

Significant level	0.1	0.05	0.01
χ^2	9.24	12.59	16.81

Table 4: Residual from Table 2

Answers \ Test bowstring	B	C	D
(1) Vibrations and impact	-1.91	-0.58	2.40 *
(2) Bowstring sound	1.84	-2.12 *	0.27
(3) Rate of bowstring recovery	0.10	1.86	-1.89
(4) Others	0.55	0.46	-0.98

* $p < 0.05$ (| Residual | > 1.96)

4. SUMMARY

We studied the effects of bowstrings of different material -- Kevlar, Technora, Vectran, and hemp -- on logarithmic decrements and frequency of vibration in the Japanese bow, energy transmission efficiency, and the archer's "feel." We also reviewed the correspondence of the archer's sensitivity to dynamic factors measured, with the following results:

(1) A comparison of logarithmic decrements in Japanese bow bending and twisting vibration clarified that hemp (D) gives the highest logarithmic decrements for both. Results of frequency analysis using FFT showed that for bowstrings of different material, power spectra of residual vibration after release are nearly identical for all subjects and trials. The effects of bending and twisting vibration on frequency are thus nearly negligible.

(2) In a comparison of energy transmission efficiency for the 4 types of bowstring, those of Kevlar (A), Technora (B), and Vectran (C) were found nearly identical at about 69%, while that of hemp (D) was

slightly lower than the others at 67.7%.

(3) Results of a questionnaire showed that answers for bowstrings significantly deviate. We found a close relationship between dynamic factors relating to logarithmic decrements of vibration, energy transmission efficiency, etc., and the archer's "feel." It may thus be argued that KANSEI Engineering technology evaluation based on measurement of dynamic factors related to release is effective in improving bowstring evaluation and "feel."

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