Surface Treatments to Increase the Perceived Vibration of a Piezoelectric foil

by

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SUBMITTED TO THE DEPARTMENT OF MECHANICAL ENGINEERING IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2000

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Submitted to the Department of Mechanical Engineering
on May 5, 2000 in Partial Fulfillment of the
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ABSTRACT

Piezoelectric polyvinylidene fluoride (PVDF) film is a semi crystalline homopolymer. When the foil is stretched the dipoles and their attached crystalline structure move -- changing the polarization of charge at the foil surfaces, thus changing the voltage across the metallized electrodes. Conversely when a voltage is applied across the electrodes the foil changes dimensions. This investigation sought surface modifications that increased subject's perceptions of vibration when they touched the foil with the right fingertip. Eight modifications, and the foil alone, were tested on five human subjects. The subjects were asked to adjust the vibration amplitude of a small speaker to match the perceived vibration amplitude of each PVDF sample as it was driven with a sinusoidal voltage (250 Hz, 240 Vpp). The adjusted RMS voltage of the speaker was taken to be a gage of the intensity of subject's perception. Six of the surface modifications worked better than the unmodified foil, ### with statistical significance ($p<0.05$, one tailed t-test, $df=8$), with the three most successful increasing perceived intensity by 10-12 dB. All the successful surface treatments incorporated a stiff mylar lamination that converted the tangential stretch of the PVDF into normal vibration that tapped (rather than stroked) the finger.

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ACKNOWLEDGEMENTS

The author would like to acknowledge James Biggs Ph.D. for his much needed guidance and direction on the project. I would also like to thank the following people for volunteering their time to participate in my experimental study: Scott DePong, Christine Neumann, and Gerda Nolan. The following people also greatly help keep me motivated while working on the project: Alexandria Phan, Stephanie Phan and Michael Rizen. In addition the author would like to thank Matt Swanson for his support and encouragement.

Introduction

1.1 Polyvinylidene Fluoride (PVDF) Foil Properties

Polyvinylidene fluoride (PVDF) film is a semi-crystalline homopolymer. A homopolymer is a polymer in a mixture of crystalline and amorphous states. One of the crystal states for PVDF is ferroelectric and thus responsible for PVDF's piezoelectric properties. The ferroelectric state of PVDF foil is created by drawing or rolling the foil and then applying a high electrostatic potential across the foil at an elevated temperature to permanently polarize the PVDF. As a result, the dipoles are aligned with the imposed electric field, normal to the surface. The PVDF foil is then cooled and a conductive coating is applied to both foil surfaces to act as electrodes.

The piezoelectric properties of PVDF foil allow it to be manipulated electrically to induce a physical change in the foil's dimensions. When an external voltage is applied across the electrodes of the PVDF foil the alteration in the polarization charge on the surface of the foil causes the dipoles and their attached crystalline structure to move and thus impart a force to the foil. The force imparted results in a change in the foil's dimensions. Conversely, if the PVDF foil is stretched the dipoles and their attached crystalline structure realign and alter the polarization charge of the foil's surface. The alteration in polarization charge appears as a voltage across the metallized electrodes.

By convention the notation for the different axis of the PVDF film is given by:

1 = length (or stretch) direction

2 = width (or transverse) direction

3 = thickness direction.

The appropriate piezoelectric coefficient for the axis of applied stress or strain is denoted by d_{3n}, where the first subscript refers to the electrical axis, while the second subscript refers to the mechanical axis. For PVDF film the voltage is usually applied across the thickness of the film and hence corresponds to a subscript of 3. The mechanical axis, however, can be 1, 2, or 3. Figure 1 contains a diagram illustrating the numerical classification of the axes.

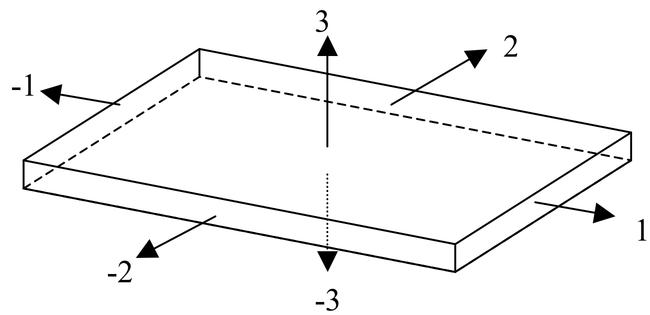


Figure 1: Numerical classification of the axes of PVDF film. The voltage is applied across the film in the axis corresponding to the 3 direction.

The change in length of the PVDF foil can be theoretically determined by applying the following equation:

$$\Delta l = l \, d_{31} \, (v/t),$$

where l is the length of the PVDF film in the 1 direction, d_{31} is the piezoelectric coefficient, v is the applied voltage, and t is the thickness of the film in the 3 direction. Because the d_{32} and d_{33} coefficients are small, changes in these directions were negligible. For the voltages (±120V) and PVDF thickness (9μm) used in this study, the theoretical d_{31} length change was approximately 3 μm

1.2 Structure and Innervation of the Human Finger

Fingertip skin is comprised of the epidermis and dermis, which overly subcutaneous fat and bone. The four types of mechanoreceptors in the dermis are Meissner's corpuscles, Merkel's discs, Ruffini endings, and Pacinian corpuscles. Pacinian corpuscles (PCs), are extremely sensitive to vibrations of 200-400 Hz, and were most likely the only receptors excited by the relatively small displacements of the PVDF in these experiments.

1.3 Potential Applications of PVDF Foil

PVDF film is thin, flexible, mechanically tough, inexpensive, and has a low density. The malleability of the foil lends itself to potentially being used as a vibration transducer in joysticks, gloves, and other tactile displays used as an interface between humans and computer simulated environments. Unfortunately, however, large displacements or forces are not possible with PVDF film alone. In order to enhance the vibratory amplitude of PVDF foil the following paper describes a preliminary investigation into possible surface treatments and mechanical designs intended to increase the perceived vibration sensation imparted to mechanoreceptors located in human fingers.

Experimental Materials and Methods

2.1 Design Methodology

Piezofoils in two basic configurations were used for the experimental study: (1) a laminated form where the foil itself was sandwiched in between two layers of mylar, and (2) an unlaminated form where the foil had only a thin insulating layer around it. Before any modifications, the motion of both the unlaminated and laminated PVDF foils were determined for excitation with a sinusoidal (240 Vpp) voltage.

For the unlaminated foil, applied voltage was calculated to cause a length change in the 2 direction of approximately 3μm, in phase with the voltage. For the laminated foil, theoretical predictions were inadequate, so the motion was measured with an optical lever. A laser beam was reflected off of the foil obliquely ($\theta \sim 70°$) and projected onto a vertical surface about 2m distant. The laser was slowly translated so that the point of reflection was scanned over the length of the PVDF foil, while the excursion of the vibrating laser spot was recorded. Points of maximum and minimum deflection were noted.

Various mechanical designs were considered for amplifying the perceived vibration of the PVDF foil. In general, the designs fell into two categories:

- **Cantilever** -- aimed at amplifying the absolute change in length and redirecting the motion from tangential to normal.

- **Relative** – aimed at attaching stiff members (wires or shims) to distant points on the foil, so that the Δl of the whole foil occurs over a smaller region (that is, the tips of the members).

These designs were executed with by attaching either thin copper wire(s) (### diameter) or steel shims (0.001 inch) to the PVDF film -- either permanently with cyanoacrylate glue, or reversibly with double sided adhesive tape.

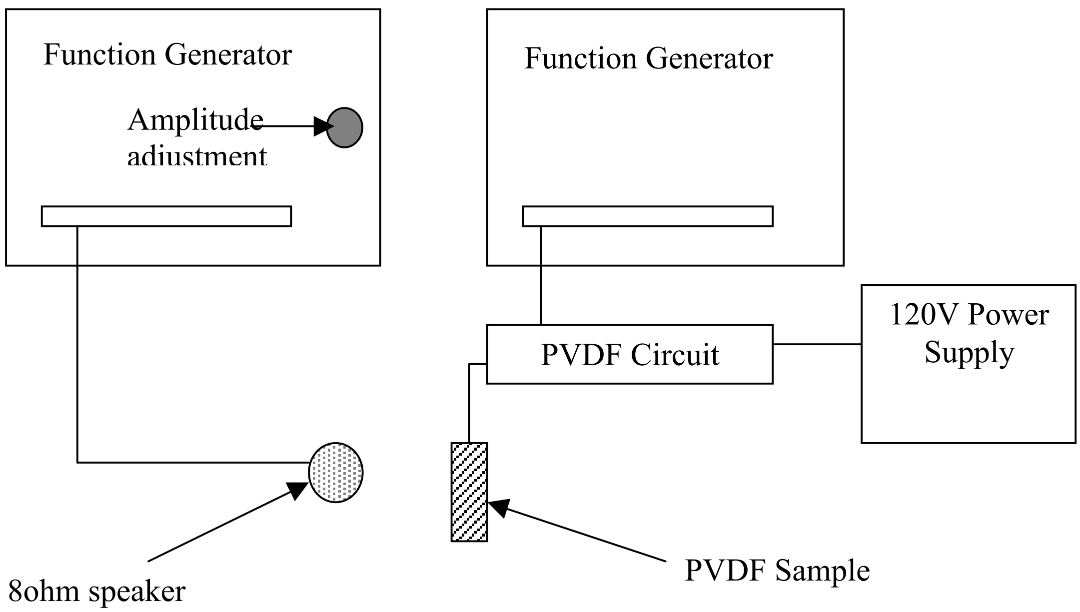


Figure 2: Experimental Apparatus: Subjects adjusted the voltage amplitude of the 8ohm speaker until the vibration output matched the perceived vibration of the PVDF sample.

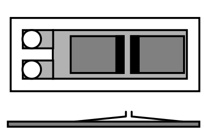
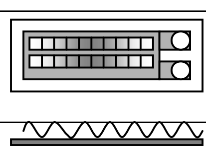
Both the laminated and unlaminated forms of PVDF foil had the same dimensions (31 by 20 mm). The relative intensity of the vibration perceived was calibrated against the vibration output of a miniature 8Ω speaker.

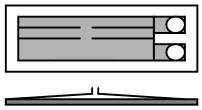
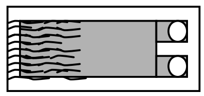
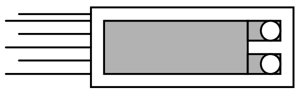
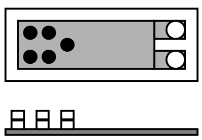
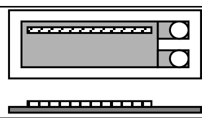
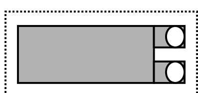
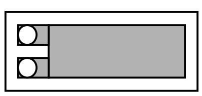
The electronics used to drive the PVDF foil were borrowed from the Interactive Balloon Project at the Media Lab, MIT. These amplified the ~20 Vpp function generator signal through two power diodes, then through a 1:10 power transformer that boosted the PVDF drive voltage to 240 Vpp. (Paradiso, 1996).

2.2 PVDF FILM TESTING PROCEDURES

A diagram of the experimental apparatus is shown in figure 2. The diagram shows that each sample of PVDF film was fixed at one end. The other end of the PVDF film was allowed to vibrate freely. Special mechanical designs that required a different experimental setup were used as needed. Table 1 lists all of the different samples tested.

Table 1: Different PVDF film configurations that were tested.

	Two metal sheets are attached to opposite ends of the unlaminated PVDF foil. At the center, where the pieces meet the ends are folded up perpendicular to the plane of the film. The folded ends are unconstrained and free to move. The change in length of the PVDF foil would result in the metal sheets moving away and towards each other at the middle of the film.
	Two thin strips of crimped metal are attached to opposite ends of the laminated PVDF foil. The other ends are left unconstrained and free to move.

	Two sets of thin copper wire are attached to opposite ends of the unlaminated PVDF foil. The other ends are bent perpendicular to the film and left unconstrained. The change in length of the PVDF foil would result in the wires moving away and towards each other at the middle of the film.
	Many overlapping layers of short copper wire are applied to the laminated PVDF foil. The wires are only attached at one end. The other end is unconstrained and free to move.
	Six strands of copper wire are attached to the very tip of laminated PVDF foil. The wires are used to extend the moment arm of the PVDF beam during vibration.
	Five small copper springs are attached to the surface of the laminated PVDF foil.
	A long copper spring is attached to unlaminated PVDF foil. The spring is only attached at the ends. The middle portion of the spring was allowed to move freely.
	Unlaminated PVDF foil with no modifications.
	Laminated PVDF foil with no modifications.

Seven human subjects were used to test the relative intensity of vibration for each of the PVDF foil samples. To quantitatively analyze the vibration amplitude of each PVDF sample the sample's vibration amplitude was compared to the vibration amplitude output of a miniature speaker.

The 8Ω speaker coil was driven with sinusoidal voltage (0-35 Vpp, 250Hz), displacing the speakers' thin flexible plastic diaphragm. The excursion of the diaphragm was taken to be a linear function of voltage, based on the following three assumptions:

1) The speaker was modeled as an ideal solenoid so that the relationship between the number of windings, N, magnetic moment of the coil, μ, current in the coil, I, and magnetic field, B is

$$B = \mu NI .$$

2) Inductance of the coil was negligible at the relatively low frequency (250 Hz) used in this study, so that the relationship between the current, I, voltage, V, depend only on the resistance, R, of the speaker is

$$I = V / R.$$

3) The force-displacement relationship of the speaker diaphragm could be modeled as a linear spring for small displacements.

The human subjects were asked to compare the perceived intensity of vibration from the PVDF sample to the amplitude vibration of the speaker. The subjects were only allowed to touch the speaker and PVDF sample with the right index finger. The subjects, however, were allowed to move their finger around until they could sense the maximum amplitude of vibration. If the two amplitudes did not match the subjects could adjust the voltage amplitude of the speaker by turning the dial on the function generator. The subjects were allowed to continuously adjust the voltage amplitude of the speaker until he/she felt that there was a match between the vibration of the PVDF sample and the vibration of the speaker. While participating in the test subjects wore headphones in order to minimize sound cues and to promote concentration.

Presentation of the PVDF samples to the subjects was random without replacement. Each PVDF sample was tested three times by each subject. The PVDF samples were presented individually to the subject in three sets. Between each set the subjects took a five to ten minute break to recover from fatigue.

Results

The results from five of the subjects testing are shown in figure 3; results of two subjects, who did not pay close attention, were excluded. Before plotting, the data were normalized to span the range (0, 1) then converted to dB, where 0dB refers to the speaker voltage that subjects used to match the perceived intensity of the unmodified unlaminated PVDF foil.

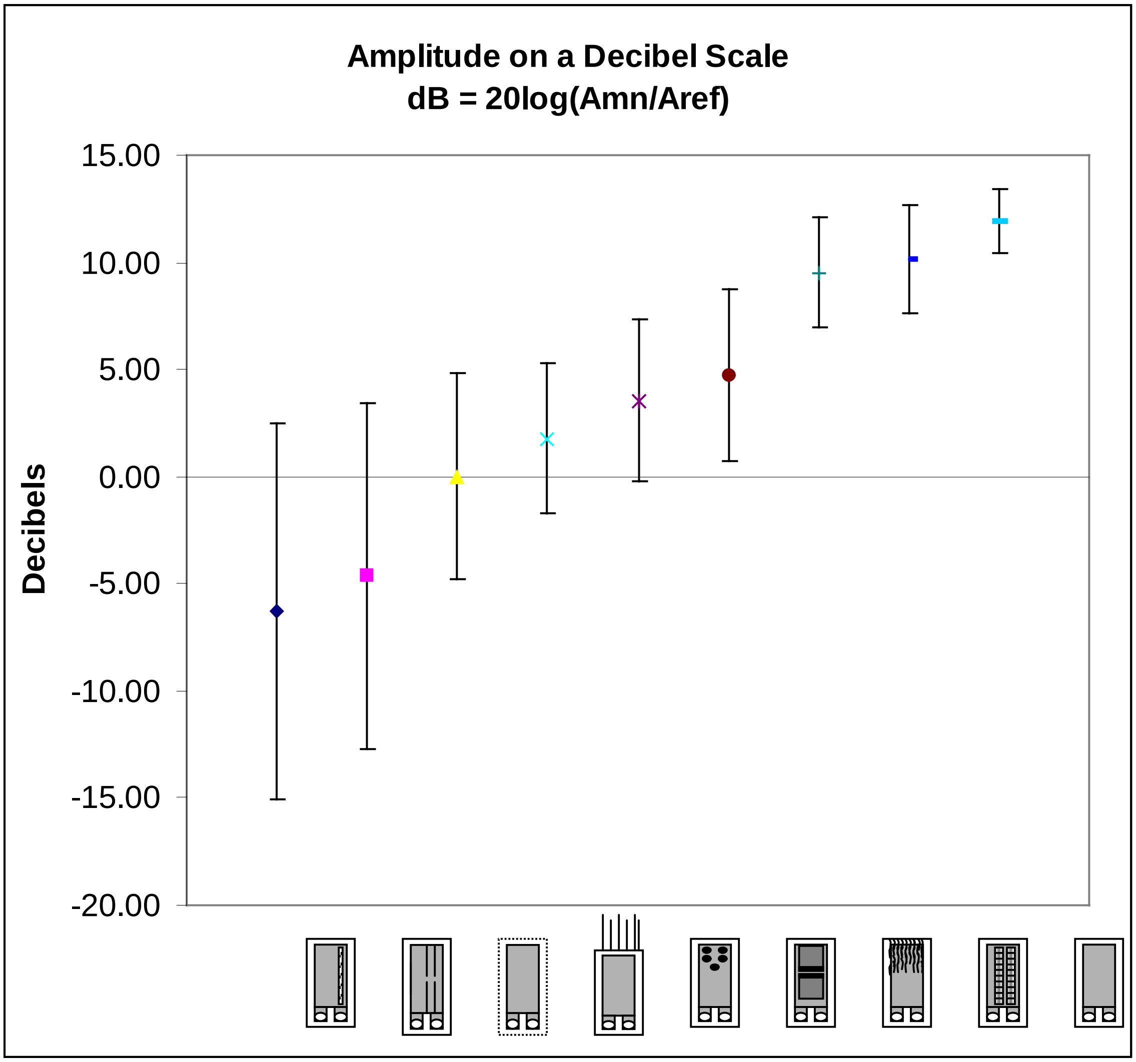


Figure 3: Speaker voltages in dB (mean ± σ) subjects used to match the perceived intensity of each PVDF sample (horizontal axis). Data are normalized to span the range (0,1), and converted to dB, where 0dB refers to the voltage subjects used to match the perceived intensity of the unmodified foil (third from left).

Figure 4 shows the results of the investigation of the laminated PVDF film's vibratory motion when a sinusoidal voltage signal is applied across the electrodes.

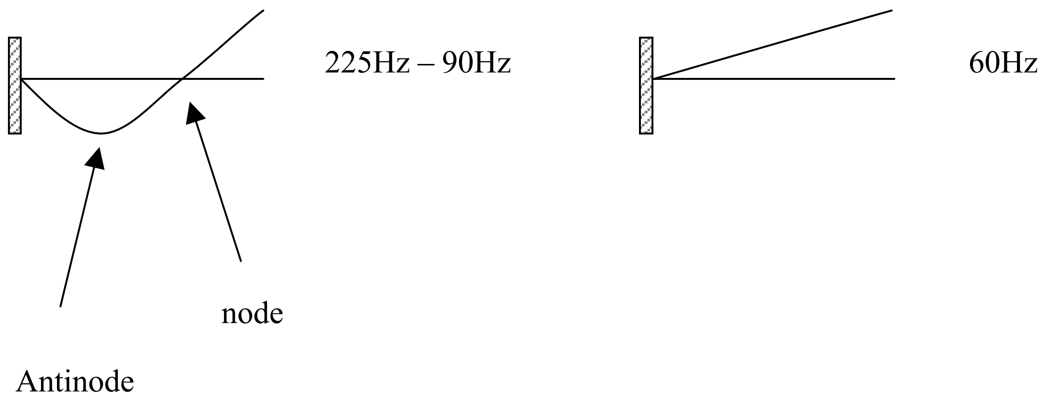


Figure 4: By scanning along the length of the laminated PVDF foil with a laser the vibratory motion of the sample at varying frequencies was determined. The points of maximum deflection of the laser beam along the length of the PVDF sample were interpreted to be an antinode. The points of minimum deflection was considered to be a node. The first mode of vibration was found to occur in the laminated PVDF sample at 60Hz. The second mode of vibration occurred between 225Hz and 90Hz.

Discussion

The data show a moderate increase in perceived vibration for most modifications of the PVDF foils. Only two of the nine sample tested failed to produce an increase in perceived vibration.

Losers

The losers were: 1) two sets of sliding copper wire, or 2) a long copper spring (1mm diameter).

It was hoped that the long copper coil (sample 1), which was attached to both ends of an unlaminated PVDF sample, would resonate in compression as the PVDF changed length by

3μm. We suspect it failed because the skin contact area was small, and skin friction kept the coils from moving tangentially.

We suspect the main cause of the failure of the sliding copper wires (sample 2) is probably the extremely small skin contact area -- only four points at the center of the PVDF film. In addition, if the subject pressed down with too much pressure the vibration of the copper wires was easily damped.

Winners

A similar PVDF sample configuration to the two sets of copper wires, however, produced positive results. The PVDF sample with many rows of overlapping short copper wires produced the third highest perceived vibration amplification relative to nominal. We conclude that the increased contact area greatly increased the perception of vibration.

The two most successful PVDF samples were the plain laminated sample and the sample with attached crimped metal strips. A possible explanation for the large increase in perceived vibration is that the frequency at which the PVDF samples were being driven might have excited a resonant mode in the crimped metal sheets and the composite laminated beam.

A common feature of the most successful PVDF samples was the cantilevered beam. The beam introduced several effects that may have increased sensation.

1) out-of-plane vibration
2) increased displacement through cantilever geometry
3) increased displacement through resonance

For the PVDF sample with two crimped metal strips, we suspect that the increase in perceived vibration was due the strips extending the moment arm of the displacement caused by the curvature of the foil. We suspect the sample with several rows of copper wires also succeed by increasing the moment arm of the PVDF foil and thus increased longitudinal deflection.

The two most successful PVDF samples also provided large relative displacements. For example, each row of overlapping copper wires was mechanically independent, and could undergo different displacements. This also increased the total number of independently vibrating objects.

Limitations of this study

The testing of the PVDF samples on human subjects was mainly to get a quick quantitative result of whether or not the sample could increase perceived vibration. As a result the testing conditions did not control for visual cues, skin temperature, and other possible sources of artifact.

Recommendations

This study showed that surface treatments can increase perceived vibration, and warrant further work. In particular, laminated PVDF foil with surface modification shows promise. In future work, we propose to imbed many small beams into the mylar lamination. The beams will be fixed at one end to the PVDF foil, leaving the other end free to vibrate at a resonant frequency of 250Hz.

APPENDIX

Data Collected from PVDF Sample Testing							
Sample	**Amplitude [V]**	**Normalized**	**Amplitude [V]**	**Normalized**	**Amplitude [V]**	**Normalized**	**Mean**
1	5.27	1.00	2.32	0.62	2.35	0.79	3.31
2	2.23	0.26	3.14	1.00	2.73	0.98	2.70
3	3.27	0.52	3.10	0.98	2.77	1.00	3.05
4	2.45	0.32	2.03	0.48	1.44	0.34	1.97
5	2.95	0.44	2.19	0.55	2.11	0.67	2.42
6	1.69	0.13	1.10	0.04	0.74	0.00	1.18
7	1.14	0.00	1.01	0.00	0.90	0.08	1.02
8	1.69	0.13	1.09	0.04	0.81	0.03	1.20
9	2.40	0.31	2.25	0.58	1.29	0.27	1.98
1	1.48	1.00	4.42	1.00	2.41	0.61	2.77
2	1.33	0.90	2.44	0.49	3.67	1.00	2.48
3	1.33	0.90	1.71	0.30	2.14	0.52	1.73
4	0.00	0.00	1.65	0.28	2.01	0.48	1.22
5	0.63	0.43	1.39	0.22	1.16	0.22	1.06
6	1.11	0.75	0.67	0.03	0.47	0.00	0.75
7	0.86	0.58	0.58	0.01	0.59	0.04	0.68
8	0.80	0.54	0.56	0.00	0.50	0.01	0.62
9	0.83	0.56	1.26	0.18	1.46	0.31	1.18
1	4.35	0.58	5.50	1.00	4.25	1.00	4.70
2	3.04	0.33	2.95	0.54	3.04	0.67	3.01
3	3.83	0.48	3.05	0.55	3.47	0.79	3.45
4	2.42	0.21	1.66	0.30	1.31	0.21	1.80
5	1.68	0.07	2.27	0.41	2.01	0.40	1.99
6	1.32	0.00	0.00	0.00	0.53	0.00	0.62
7	1.95	0.12	2.33	0.42	1.93	0.38	2.07
8	2.30	0.19	1.98	0.36	1.88	0.36	2.05
9	6.53	1.00	2.44	0.44	2.55	0.54	3.84
1	3.97	1.00	3.34	1.00	3.68	1.00	3.66
2	2.24	0.56	2.83	0.85	3.07	0.83	2.71
3	3.00	0.76	2.16	0.65	2.67	0.73	2.61
4	1.26	0.32	1.40	0.42	1.24	0.34	1.30
5	1.30	0.33	1.74	0.52	1.47	0.40	1.50
6	0.90	0.23	1.00	0.30	1.04	0.28	0.98
7	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	1.10	0.28	1.38	0.41	1.08	0.29	1.19
9	0.83	0.21	1.10	0.33	1.47	0.40	1.13
1	3.14	0.88	3.60	1.00	2.78	0.71	3.17
2	3.45	1.00	2.63	0.66	2.79	0.71	2.96
3	1.85	0.39	2.04	0.46	3.66	1.00	2.52
4	1.17	0.14	1.08	0.13	1.07	0.15	1.11
5	1.10	0.11	0.97	0.09	1.16	0.18	1.08
6	1.00	0.07	0.82	0.03	0.90	0.10	0.91
7	0.81	0.00	0.72	0.00	0.61	0.00	0.71
8	1.09	0.11	1.71	0.34	1.37	0.25	1.39
9	1.82	0.38	1.00	0.10	1.08	0.15	1.30

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