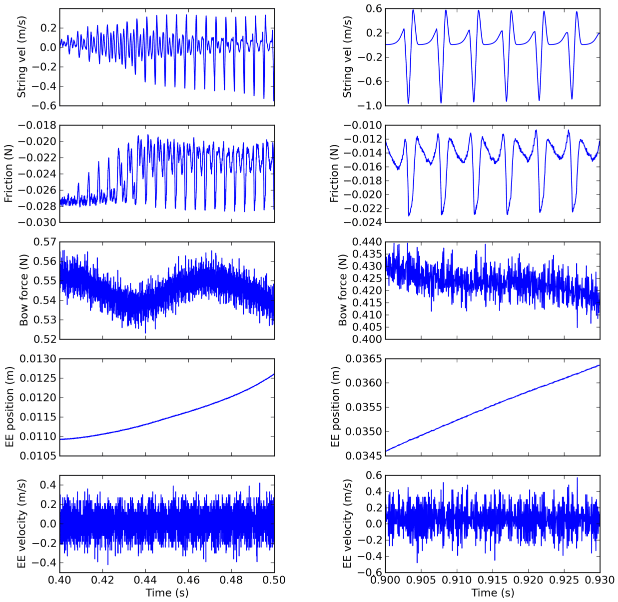

Figure 11: Two zoom levels of a recording of DISTPLUCK running at 30 kHz on a haptic device. From top to bottom, the plots are: string velocity v_s, friction force, normal force, horizontal position of end effector, and velocity estimated by backward difference.

off the string. Both of these issues are currently under investigation and will be the subject of future work.

To more completely characterise this work, it is necessary to further examine the behaviour under known conditions in bowed string physics. There are several techniques that have been used to evaluate numerical models of bowed strings [18]: checking the model against Shelleng's playability diagrams, which characterise oscillation regimes in terms of force and β-ratio parameters; verifying the emergence of a "flattening effect" at certain parameters, described in [18] (a sudden drop in frequency due to hysteresis); and the characterisation of raucous motion at hard normal force, to name a few.

Since the quality of a sounding model can be hard to judge objectively, blind evaluations with professional string players should be performed to establish preferences under various conditions and fundamental frequencies. For instance, as mentioned, the human frequency discrepancy between modalities provides room to make use of velocity filtering in order to improve the estimate; since the bowed string naturally exhibits some noise due to the physical characteristics of the bow's horse hair, it is not known where the threshold of acceptability lies for the existence of noise in the resulting sound. This noise-free algorithm could provide a baseline for comparison. Such a threshold would provide a target error margin for velocity measurement that could be taken into consideration for future device development, simplifying the implementation of velocity-based effects.

7 Acknowledgements

This work was funded by a grant from the Natural Sciences and Research Engineering Council of Canada (NSERC) and MPB Technologies Inc. to the first author, as well as by a grant from the NSERC "Enactive" special research opportunity.

References

[1] S. Barrass and M. Adcock. Interactive granular synthesis of haptic contact sounds. In *Proceedings of the AES 22nd International Conference on Virtual, Synthetic and Entertainment Audio*, pages 270–277, Helsinki University of Technology, Espoo, Finland, June 2002.

[2] E. Berdahl, G. Niemeyer, and J. Smith, III. Using haptic devices to interface directly with digital waveguide-based musical instruments. In *Proceedings of the Ninth International Conference on New Interfaces for Musical Expression, Pittsburgh, PA*, pages 183–186, 2009.

[3] R. H. Brown, S. C. Schneider, and M. G. Mulligan. Analysis of algorithms for velocity estimation from discrete position versus time data. *IEEE Trans. on Indus. Elec.*, 39(1):11–19, Feb. 1992.

[4] P. R. Cook and G. Scavone. The synthesis toolkit (STK). In *Proceedings of the International Computer Music Conference*, pages 164–166, 1999.

[5] P. R. Dahl. Solid friction damping of mechanical vibrations. *AIAA Journal*, 14(12):1675–1682, 1976.

[6] D. DiFilippo and D. K. Pai. The AHI: An audio and haptic interface for contact interactions. In *Proceedings of the 13th Annual ACM Symposium on User Interface Software and Technology*, pages 149–158, 2000.

[7] J. Florens, A. Luciani, C. Cadoz, and N. Castagné. ERGOS: Multi-degrees of freedom and versatile force-feedback panoply. In *Proceedings of Eurohaptics*, pages 356–360, 2004.

[8] J.-L. Florens. Expressive bowing on a virtual string instrument. In A. Camurri and G. Volpe, editors, *Lecture Notes in Computer Science: Gesture-Based Communication in Human-Computer Interaction, 5th International Gesture Workshop*, volume 2915, pages 487–496. Springer Berlin / Heidelberg, Genova, Italy, April 2003.

[9] V. Hayward and B. Armstrong. A new computational model of friction applied to haptic rendering. In *Proceedings of The Sixth International Symposium on Experimental Robotics VI*, pages 403–412, London, UK, March 2000. Springer Verlag.

[10] F. Janabi-Sharifi, V. Hayward, and C.-S. J. Chen. Discrete-time adaptive windowing for velocity estimation. *IEEE Trans. on Cont. Sys. Tech.*, 8(6):1003–1009, Nov. 2000.

[11] C. Nichols. The vBow: development of a virtual violin bow haptic human-computer interface. In *Proceedings of the Conference on New Interfaces for Musical Expression*, pages 29–32, Dublin, Ireland, 2002.

[12] S. Serafin, C. Vergez, and X. Rodet. Friction and application to real-time physical modeling of a violin. In *Proceedings of the International Computer Music Conference*, pages 375–377, Beijing, China, 1999. ICMA.

[13] S. Sinclair, J.-L. Florens, and M. M. Wanderley. A haptic simulator for gestural interaction with the bowed string. In *10ème Congrès Français d'Acoustique*, Lyon, France, Apr. 2010. SFA.

[14] S. Sinclair, G. Scavone, and M. M. Wanderley. Audio-haptic interaction with the digital waveguide bowed string. In *Proc. of the International Computer Music Conference*, pages 275–278, Montreal, Canada, 2009.

[15] J. Smith and J. Woodhouse. The tribology of rosin. *Journal of the Mechanics and Physics of Solids*, 48(8):1633–1682, 2000.

[16] J. O. Smith. Synthesis of bowed strings. *The Journal of the Acoustical Society of America*, 71(S1):S101, April 1982.

[17] K. van den Doel, P. G. Kry, and D. K. Pai. FoleyAutomatic: physically-based sound effects for interactive simulation and animation. In *Proceedings of the 28th annual conference on computer graphics and interactive techniques*, pages 537–544, 2001.

[18] J. Woodhouse. Bowed string simulation using a thermal friction model. *Acta Acustica united with Acustica*, 89:355–368, 2003.