A Self-Sensing Vibrotactile Transducer for Bidirectional Tactile Interaction

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Abstract. An approach to achieving simultaneous, collocated vibrotactile haptic feedback and tactile sensing is presented. A single voice coil transducer is used for sensing transients such tap strikes and taps by a fingertip, along with continuous surface pressure. A current drive amplifier provides the actuation signal. A digital filter configuration is used to cancel the actuation signal from the voltage sensing signal by modelling the transducer's impedance. The possible benefits of the system within digital musical instrument (DMI) design are briefly discussed.

Keywords: vibrotactile · self-sensing · collocation · haptic feedback

1 Introduction

Human touch is bidirectional – a single contact point enables simultaneous sensing of tactile elements and actuation through movement. This can enable tight haptic couplings – whereby energy is exchanged in a bidirectionally between human and object. This paper presents a method of creating tightly coupled haptic interactions using vibrotactile haptic feedback, with a single voice coil transducer used for both sensing and actuation.

The self-sensing technique presented in this paper utilises the impedance characteristics of a voice coil transducer, by providing actuation using a current drive amplifier and sensing by measuring the voltage across the transducer. Through using known features of the transducer's impedance, three uses can be achieved simultaneously: wide-band vibrotactile haptic actuation using the current drive amplifier, sensing of pressure upon the transducer by measuring changes in the transducer's resonance, and acting as a pickup for transient excitation signals from the user striking the transducer with a fingertip. This technique enables wide-band, audio rate, and low latency actuation and sensing of the excitation signal. This enables close integration with musical synthesis software, for instance, with high bandwidth, tightly coupled haptic interactions.

2 A Self-Sensing Approach

While achieving bidirectional tactile interaction is possible using separate components for sensing and actuating, the use of a single electrical component to achieve both tasks has certain advantages due to its perfect collocation of sensing and actuating position [6]. Firstly, this prevents any occlusion between the two elements of sensing and actuating - the actuator surface is not blocked or masked by any sensing element. Secondly, the relationship between the actuation signal and sensor signal can be modelled in the electrical domain, without needing to account of any complex mechanical elements such as mechanical propagation delay between the actuator and sensor [1].

Previous work on self-sensing configurations has often utilised time division multiplexing between sensing and actuation using a single transducer to achieving perceptually simultaneity [5]. Prior research has also shown techniques using a transducer's voltage-current duality to achieve simultaneous sensing and actuation with linear resonant actuators for narrow-band vibrotactile haptic feedback [4] along with applications in other areas of feedback control outside of the haptic feedback domain [6].

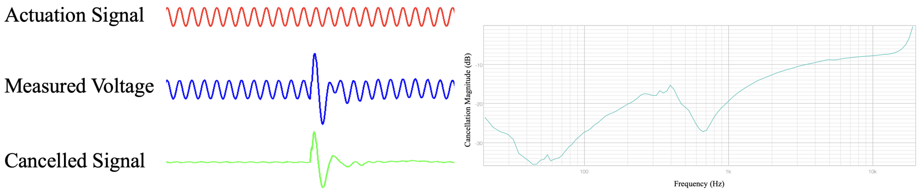
3 The Prototype System

A voice coil transducer's mechanical properties can be modelled as equivalent electrical components, leading to an equivalent electrical circuit representation incorporating both the voice coil's electrical and mechanical characteristics [2]. The electrical impedance of a voice coil transducer is determined by the equivalent circuit's component values. Such transducers exhibit a peak in impedance at a resonant frequency (f_0). The frequency, quality factor, and maximum value of the peak in impedance is determined by the transducer's compliance, moving mass, and mechanical damping.

The presented haptic system uses a transconductance current drive amplifier design from [7]. Signal processing of both the actuation and measured voltage signals is implemented on a Bela Mini [9]. The voice coil transducer used during development was a Tectonic TEAX25C10-8/SP surface exciter, designed to be used as a loudspeaker when mounted to a rigid surface, though also suitable for use as a wide-band haptic transducer.

To sense the continuous force applied upon the transducer by the musician, the change in impedance at f_0 is measured. A constant tone of frequency f_0 is added to the actuation signal, providing a constant signal to measure. The Goertzel algorithm (effectively a single bin of a DFT) is used to measure the signal level at f_0 from the Voltage across the transducer. When pressure is applied to the transducer, increasing the mechanical damping, the peak in impedance is reduced, leading to a reduction in level at f_0. While the use of the Goertzel algorithm limits the control output rate to the period of a window size, rather than a low latency audio-rate output, the perceptually acceptable action-sound latency requirements for continuous gestural controls (of which the pressure sensing is an example) is deemed to be 20-30ms, higher than that of transient interaction (10ms) [8].

Alongside sensing continuous pressure, the system also enables the transducer to act as a pickup simultaneously – with audio rate excitation signals from the transducer for use in DMI designs, for example. This requires the actuation signal to be cancelled from the voltage across the transducer, to avoid a feedback loop. To cancel out the actuation signal from the measured voltage signal, a filter system that models the voice coil's equivalent electrical circuit must be created. By splitting the actuation and sensing into current and voltage domains respectively, the transfer function between the actuated and sensed signals is directly proportional to the transducer's impedance. The filter model uses a biquad peak filter to model the resonance of the system, with a one pole filter to model the rise in impedance at high frequencies due to the inductance of the voice coil. The actuation signal is sent to the transconductance amplifier and the filtering setup in parallel. The filtered signal is subtracted from the voltage input signal, cancelling the actuation signal from the input. An example of this can be seen in Figure 1a, where the 100Hz sine tone actuation signal is removed from the voltage signal, leaving only the finger tap. Figure 1b shows the amount of cancellation achieved against frequency.



(a) Time domain with tap and cancelled tone (b) Cancellation magnitude across frequency

Fig. 1: Cancellation shown with example signal and cancellation across frequency

The vibrotactile system described in this paper has been demonstrated as an interaction method for controlling a physical modelling synthesiser in ongoing work [3]. Future research will explore the creative possibilities of this technology within a DMI design.

Acknowledgments. This work is supported by a UKRI Frontier Research grant (EP/X023478/1) “RUDIMENTS: Reflective Understanding of Digital Instruments as Musical Entanglements.”

Disclosure of Interests. The authors have no relevant competing interests to declare.

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