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An ultrasonic transducer transient compensator design based on a simplified Variable Structure Control algorithm

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ABSTRACT

A non-linear control method, known as Variable Structure Control (VSC), is employed to reduce the duration of ultrasonic (US) transducer transients. A physically realizable system using a simplified form of the VSC algorithm is proposed for standard piezoelectric transducers and simulated. Results indicate a VSC-controlled transmitter reduces the transient duration to less than a carrier wave cycle. Applications include high capacity ultrasound communication and localization systems.

1. Introduction

This research on acoustic data transmission was initiated to assess the large potential benefits from applying encoding concepts used in radio communication, to US systems. Much of the electromagnetic spectrum is strictly regulated to control the performance and interference generated by communication systems. Furthermore, radio systems are not appropriate in some environments. Improper use of radio systems in the inflammable atmosphere of petro-chemical plants [1], or mines, can lead to serious accidents. Radio interference in hospitals can lead to the malfunction of life-critical systems. The US spectrum is minimally regulated and is an alternative to wireless systems for data or voice transfer, through air, over short distances up to 20 m in indoor environments.

A small number of US systems utilize the encoding and modulation schemes common in radio systems, but only achieve limited data transmission rates of a few kilo bits per second (kbps), see [2,3]. Previous research has demonstrated that it is possible to use an air-coupled transducer with a center frequency below 100 kHz. Conventional US systems are able to transmit an amplitude-modulated US wave with a carrier frequency in the range of 25–100 kHz [4]; and these have been used for television remote control [5–7]. Broadband transducers, with a frequency range from 100 kHz to 1 MHz and a bandwidth up to 500 kHz, can be manufactured using a range of processes including thin film (polymer membrane) [8], electromechanical film (EMFi) [9] and micro-machined transducers [10]. These can be used in the applications where a short pulse width and high resolution are required [4], over shorter paths. These transducers are similar in their constructions in that an electric field is applied across them through contact electrodes. These electrodes, by their nature, lead to capacitive electrical coupling to the transducer.

Li et al. [4] demonstrated US communication in the air for digital data over a few meters. Modulation was based on binary encoding and used a polymer membrane transducer with the central frequency of 250 kHz with an approximate useable bandwidth of 200 kHz [4]. Li also investigated the applicability of a quadrature modulation scheme on micro-machined US transducers with a central frequency of 350 kHz and a wider band width [11]. Currently this technology is regarded as impractical for general use due to its low energy electromechanical conversion efficiency. Experiments in [11] demonstrated that a 200 V peak-to-peak electrical stimulus at the transmitter yielded a received signal with magnitude of 5 mV over a range of 1.2 m.

Air-coupled US transducers, based on the most common and cheapest piezoelectric technology, currently utilize narrow bandwidths around the resonant frequency, as the electro-mechanical inertia within the transducers leads to transients with long decay times. Fig. 9(b) is the resulting waveform when the input is a typical 40 kHz Binary Phase Shift Keying (BPSK) test signal with a 2 kHz bit rate. Note that the acoustic output takes many carrier wave cycles to synchronize with the drive message signal after a phase shift. This long duration transient limits the capacity of US communications system. A challenging problem is the generation of an acoustic signal with rapid transition between symbols. This

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requires a broad bandwidth transducer to achieve the rapid phase transitions required for phase encoding such as BPSK. Broadband transducers at higher frequencies can provide sufficient bandwidth but are more expensive and require high voltage driving circuitry. Narrow bandwidth US transducers are much more common and cheaply available and would have many applications in communication and positioning systems. However, high Q resonant US transducer can be used in these areas if only the fundamental ringing problem is resolved. The goal of this work is to reduce the ringing to less than a period of the resonant frequency.

Various methods to reduce the response time have been investigated in similarly damped systems [12–14]. Wang and Tang [15] used pulse-amplitude modulated drive signals to stimulate the transducer. Others [16] suggested pre-filtering the drive signal with the complementary transducer transfer function. This was shown to be an effective solution and yielded a compensated but time-delayed response, with a narrow pulse width in the time domain. However, the damping of the resonance depends entirely on the transducer dynamical properties and is susceptible to parametric variations, both between transducers and over time. Variable Structure Control (VSC) using high speed switching has been successful in reducing the transient response of system dynamics in a variety of applications, can be physically realized, and is robust to parameter variation [17]. The development of a feedback control system to decrease the transient duration has immediate application in improving the performance of all these US systems.

In this paper we compare an US transmission system with and without VSC and quantify the reduction in transient response time. A minimal implementation of the VSC algorithm is used that can be readily realized in microcontrollers. This paper extends the work described in [18] focusing on the design approach of a transducer VSC transient compensator by investigating the effect of sampling rate. A subsequent paper will examine VSC control of US receivers and the capacity of US communication systems.

2. Introduction to the simplified VSC system

The primary objective of applying Variable Structure Control is to provide dynamical feedback compensation to reduce the decay time of a transducer transient response. Essentially, the VSC combines the useful regions of two phase portrait trajectories, one stable and the other unstable, to obtain a specific, approximately first order, system error response; as defined in Fig. 2(b). The equivalent phase plane representation of the desired response is shown in Fig. 2(h) and is known as the *switching line* (*sw*). The combination of different system dynamics can be physically realized by switching between two feedback configurations. The feedback loop of the system block diagram in Fig. 1; through blocks *F*, *A*, *G* and *H*, provides negative feedback and the loop *F*, *B*, *G* and *H* yields positive feedback. The feedback signal, *Hy*, is a measure of the acoustic output of the transducer. Table 1 gives the definitions of system elements and signals used in Fig. 1.

Techniques for the design of a VSC *sw* are described in [19] and the principal operation of the VSC is illustratively summarized in Fig. 2. The realization of the *sw*, in this design, is based on a discrete phase portrait [20] [21]. This is defined by the sampled error signal, $e \equiv (Fr\text{–}Hy)$, discretized with a sample period, ΔT. The discrete phase plane portrait is the locus of samples of the points $(\Delta e/\Delta T, e(n-1))$. The derivative of the error is approximated by a backward difference formula: $\Delta e/\Delta T \equiv (e(n) - e(n-1))/\Delta T$, where $e(n) \equiv e(n\Delta t)$.

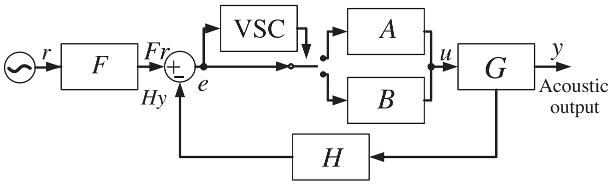

Fig. 1. Block diagram of the VSC transmitter system.

The sampling frequency should be much higher than the system resonant frequency to obtain an adequate description of the system dynamic. A mathematical expression of the discrete $sw \equiv sw(n)$ mapping in Fig. 2(h) is defined in (1) and the switching boundary is defined by (2):

$$sw \equiv (e(n) - e(n-1))/\Delta T + c_{tran} * e(n-1) \tag{1}$$

$$sw = 0. \tag{2}$$

where the constant c_{tran} is a positive slope which is related to the first order transient response decay time. The *sw* occupies the second and fourth quadrants of the phase plane.

The system error is proportionally amplified by either the negative feedback gain *A*, or positive feedback gain *B*, and then delivered to drive the transducer. The selection of positive or negative feedback paths is determined from the phase position in the phase plane, which is partitioned into four regions by the lines $\Delta e/\Delta T = 0$ and $sw = 0$:

Region *I*: $e(n-1) \geqslant 0$, $sw > 0$.
Region *II*: $e(n-1) < 0$, $sw \geqslant 0$.
Region *III*: $e(n-1) \leqslant 0$, $sw < 0$.
Region *IV*: $e(n-1) > 0$, $sw \leqslant 0$.

The driver output signal, *u*, acts as negative feedback compensation to suppress the increase of absolute magnitude of the error when the system phase trajectory is found in region *I* and *III*. This output will be switched to positive feedback compensation when the product of these two signals is negative, in region *II* and *IV*.

$$u = -A * e, e(n) \in I \cup III, \text{ or } u = B * e, e(n) \in II \cup IV. \tag{3}$$

A system dynamic, known as *quasi-sliding mode*, occurs when frequent switching between feedback modes causes the phase point to "slide" along the *switching line* toward the origin. For a discrete VSC system, the system dynamics can only be kept in a neighborhood around $sw = 0$ because of the finite speed of a feedback configuration switching which is limited to the sampling period, ΔT [21].

To achieve *quasi-sliding mode*, both feedback paths must yield phase trajectories as illustrated in Fig. 2(j). The dynamic of each closed-loop feedback configuration is assumed to be predominantly second order. In the phase plane, the second order closed-loop dynamics should be chosen to give a *stable focus* trajectory illustrated in Fig. 2(g) for the negative feedback path and a *saddle point* trajectory illustrated in Fig. 2(i) for the positive feedback path [22]. Note that to achieve each of the desired phase trajectories the closed-loop system poles must be carefully selected. This in effect is a basic way of ensuring reachability to the *sw*, in that both feedback configurations conspire to trap the overall system phase trajectory in the neighborhood of the *sw*. A *root-locus* analysis technique is used to design dominant feedback dynamics to ensure this. For the negative feedback arrangement, the closed-loop poles must be dominated by two complex conjugate poles of adequate speed to achieve a *stable focus* phase trajectory. For the positive feedback arrangement, the closed-loop system pole set must be dominated by two real poles with one in the left half of the Laplace plane and the other in the right half plane to obtain a *saddle point* trajectory. The major design problem in the VSC control system is the selection of the required gains for the feedback paths, *A* and *B*.