SOME PHYSICAL AUDIO EFFECTS

Edgar Berdahl, Julius O. Smith

CCRMA, Stanford University
Stanford, CA 94305, USA
{eberdahl|jos}@ccrma.stanford.edu

ABSTRACT

This paper presents a survey of various audio effects that can be physically applied to a rigidly-terminated vibrating string. The string's resonant behavior is described, and then the ability of active feedback control to "reprogram" the physics of the string is explained. Active damping, which is a direct result of applying classical control techniques, provides for an effect based on amplitude modulation (AM). Traditional electric guitar sustain techniques are elaborated upon, which suggest another approach for ensuring marginal stability of the system even in the presence of an arbitrary nonlinear and/or time-varying effect unit in the feedback loop. This approach involves placing a dynamic range limiter in the feedback loop and does not introduce significant harmonic distortion other than that due to the effect unit. The maximum RMS level of the system's output can be easily bounded if reasonable conditions are met by the dynamic range limiter. Finally, nonlinear and time-varying feedback control loops are applied experimentally to artificially induce frequency modulation (FM) at a low rate and AM at a high rate. These effects can be interpreted musically as vibrato and as a sort of resonant ring modulation, respectively.

1. INTRODUCTION

The study of *modal stimulation* is the study of actively controlling the vibrating structures in a musical instrument with the intent of altering its musical behavior [1]. Although it is possible to design an instrument such that most aspects are easily controllable, this study instead applies control engineering to a core component found in the guitar, the vibrating string. Many different controllers are conceivable, so we will focus on some of those relating to audio effects that have traditionally been popular among musicians. In developing some effects, we strive to preserve the musical qualities of the string that have historically been optimized during the evolution of stringed instruments. In developing other effects, we apply nonlinear and time-varying feedback loops to break free from the standard behavior of a vibrating string. In a sense, we are "reprogramming" the physics of the vibrating string. However, to simultaneously preserve the identity of the stringed instrument, we wish for the controller parameters to be as orthogonal as possible to the string length, which is adjusted by the musician during play.

2. PRIOR WORK

Various forms of actively-controlled musical instruments have been designed. For instance, the problem of indefinitely sustaining string vibration has long been investigated, especially in the framework of the electric guitar. Musicians have used acoustic feedback from loudspeakers to re-excite their electric guitar strings [2]; however, due to the complex nature of the transfer functions involved and the nonlinear nature of the amplifiers, this approach has proven difficult to control precisely. The commercially-available Sustainiac has mitigated these problems somewhat using a phase-locked loop [3]. In a similar manner, Weinreich and Caussé have electromechanically induced the Helmholtz "stick-slip" bowing motion in a vibrating string without using an actual bow [4]. Besnainou applied active feedback control techniques to a violin, a snare drum, a pipe organ, and a marimba bar [1]. For example, he changed the damping time and pitch of a marimba bar using Proportional-Integral-Derivative (PID) control.

3. OVERVIEW

To simplify matters, this study involves only a single guitar string. It is actuated electromagnetically and sensed piezoelectrically to avoid direct feedback from the actuator to the sensor [5]. The system block diagram is shown in Figure 1. $g(t)$ is the impulse response of the string and changes whenever the musician alters the length or damping of the string. k_G is the loop gain, and $r(t)$ is the plucking excitation for the string produced by the musician.

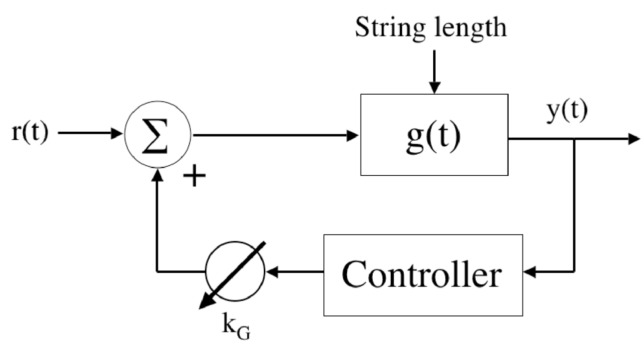

Figure 1: *System block diagram for one string.*

When no control is applied ($k_G = 0$), the string can be seen as a parallel bank of resonances at the partial overtone frequencies [5], which are approximately integer multiples of the lowest resonance frequency ("harmonics"). Applying white noise to the actuator causes all of the string's harmonics to be excited. On the other hand, large sinusoidal inputs can produce interesting behavior due to the guitar string's nonlinear nature. For example, even though a single input sinusoid can be tuned to only one of the harmonics, nonlinear interactions cause some of the energy to bleed over into the other harmonics. We can observe many of the same nonlinear effects in our guitar string that Roger Hanson has observed in a brass harpsichord string [6].

4. ACTIVELY DAMPING THE STRING

4.1. Summary

In general, removing energy from a system is more difficult than adding energy, so active damping is a problem one should consider when placing actuators and sensors [7]. Figure 2 shows how the actuator (see Figure 2a) is placed near the string termination and the sensor (see Figure 2b) is placed at the string termination. This allows the musician to change the length of the string without greatly affecting the relative distance between the actuator and sensor.

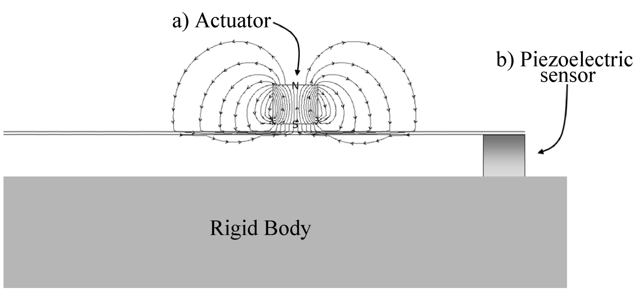

Figure 2: *Sensor and actuator placement.*

By exerting a force proportional to the integral of the string's displacement, the string can be damped quickly. This method damps the lowest harmonics the fastest. In particular, the change in the decay rate of a resonance (*i.e.*, the change in the inverse of the decay time τ) due to integral control is approximately inversely proportional to f^2, where f is the natural frequency of the resonance.

$$\Delta(1/\tau) \propto \frac{k_G}{f^2} \tag{1}$$

4.2. Amplitude Modulation

Approximate amplitude modulation (AM) of the string's displacement can be induced by varying k_G at f_c Hz:

$$k_G(t) = g \cdot \cos(2\pi f_c t) + k_{GO} \tag{2}$$

The parameter g can be used to control the intensity of the effect. Choosing $k_{GO} > 0$ ensures that plucked tones decay over time. Guitar effect units that implement this effect for f_c in the range $\frac{1}{2} < f_c < 5$ Hz refer to it as *tremolo*.

5. SUSTAINING THE STRING'S VIBRATION

5.1. Using Integral Control

One might imagine that by carefully adapting $k_G(t)$ over time while restricting $k_G(t) < 0$, one could sustain a plucked string's vibration arbitrarily long. This is equivalent to introducing a dynamic range limiter (a signal processor that limits the RMS signal level flowing through it) into the feedback loop [8]. However, due to idiosyncrasies in the system, one harmonic mode always dominates, having a tendency to grow faster than the other modes. The limiter enforces a bound on the signal level, and so eventually only the dominant harmonic remains. By this time, the sustained pluck no longer sounds like an instrument because it is devoid of rich harmonic content. This explains why the Sustainiac contains a phase-locked loop (PLL). After enough time following a pluck elapses, only the dominant harmonic will retain significant energy, and so the control algorithm may as well be simplified such that it excites the string with a sinusoid [3].

5.2. Using An Output Power-Limiting Nonlinearity

Electric guitar players have a solution for sustain in which they increase the output volume of their power amplifiers until the sound waves from the loudspeaker are powerful enough to excite the guitar strings, effectively sustaining their vibration. These systems tend to be quite complicated because they include delays, such as the air transmission delay T_d corresponding to the distance between the electric guitar player and the loudspeaker [9]. In addition, a real power amplifier has a maximum output power level, implying that the amplifier becomes nonlinear at large amplitudes. This means that at large amplitudes, the effective loop gain decreases until the energy in the system stops growing. Figure 3 shows the block diagram for the nonlinear guitar amplifier control system [10].

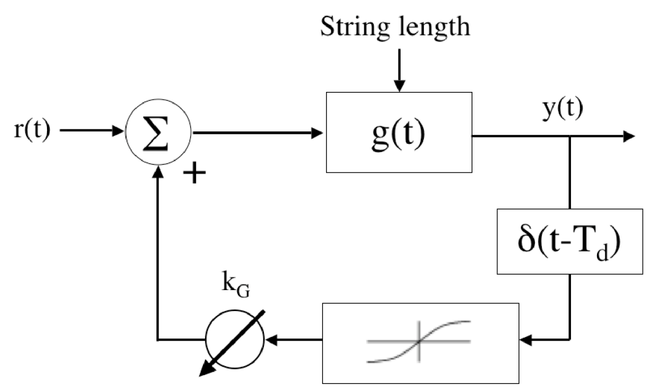

Figure 3: *Nonlinear amplifier controller configuration.*

Because the system is so nonlinear, the output does not decay to a pure sinusoid, but rather to a harmonic mixture, which may be more or less rich-sounding depending on the particular system parameters. This mixture is often desirable for artistic reasons; however, significant harmonic distortion changes the system's dynamic behavior drastically. In order to investigate other feedback effects more transparently, free from the side effects of the nonlinear amplifier method for ensuring marginal stability, an approach involving a dynamic range limiter is more palatable.

6. SUSTAINING AN ARBITRARY EFFECT

6.1. Using A Dynamic Range Limiter

The nonlinear amplifier element can be replaced by a dynamic range limiter, which adjusts the gain more slowly in order to avoid introducing significant harmonic distortion. Figure 4 depicts the system block diagram that allows for sustaining an arbitrary effect, where only the effect unit (depending on what type of signal processing it implements) can cause significant harmonic distortion.

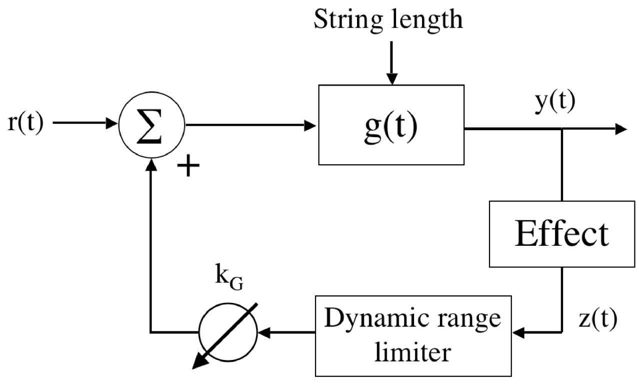

Figure 4: *Configuration for sustaining an arbitrary effect.*

6.2. Marginal Stability

In order to provide sustain, the controller should make the system marginally stable. The conditions for marginal stability are however more complicated than sufficient conditions for avoiding system instability, which will be derived here. For simplicity, we will assume that the dynamic range limiter adjusts the gain according to z_{RMS}, the RMS level of $z(t)$. We will further assume that the static compression curve of the (feedforward) limiter is upper-bounded by l and that the attack time for the limiter is essentially zero seconds. This means that the input to the string has a maximum RMS level of $r_{\text{RMS}} + k_G l$, where r_{RMS} is the RMS level of $r(t)$. Because the guitar string itself is passive, we have that $y_{\text{RMS}} \leq G_{\text{MAX}}(r_{\text{RMS}} + k_G l)$, where $G_{\text{MAX}} < +\infty$ is the maximum RMS gain of the actuator-string-sensor system represented by $g(t)$. r_{RMS} must surely be upper-bounded because a physical string can only be plucked or struck finitely hard, so y_{RMS} must also be upper bounded. Thus, we avoid system instability.

6.3. Frequency Modulation

The musical effect of applying frequency modulation (FM) to the harmonics of a guitar string is termed *vibrato* for carrier frequencies f_c roughly in the range $\frac{1}{2} < f_c < 5$ Hz. FM can be implemented using PID control of the string displacement; however, this method is quite sensitive to the particular decay rates of the harmonics of $g(t)$ [7]. Another method involves placing the cascade of an integrator and a vibrato effect unit in the feedback path. Without the integrator, the system would easily become unstable; the integrator ensures that string plucks decay quite quickly. A good compromise involves placing a dynamic range limiter in series with the effect unit (comprised of vibrato and integrator) as shown in Figure 4. Since the limiter will not be able to completely even out the volume level, some additional AM is expected.

Our implementation includes the vibrato circuit in Anderton's book [11] and the DOD Compressor Sustainer FX80B. The FX80B has an attack time of about 12ms at 500Hz, which is short enough to ensure marginal stability of the relatively well-behaved effect units that we use. That is to say, the parameters of the effect units vary slowly enough in time, and the effect units do not have wildly-varying gains due to nonlinearities. The sonogram of a guitar pluck with $f_0 \approx 250$ Hz is displayed in Figure 5. The decay of the string pluck is induced by gradually decreasing k_G to zero. It can be readily seen that the frequencies of the lowest four harmonics vary periodically. Note that the energy at 120 Hz is measurement noise.

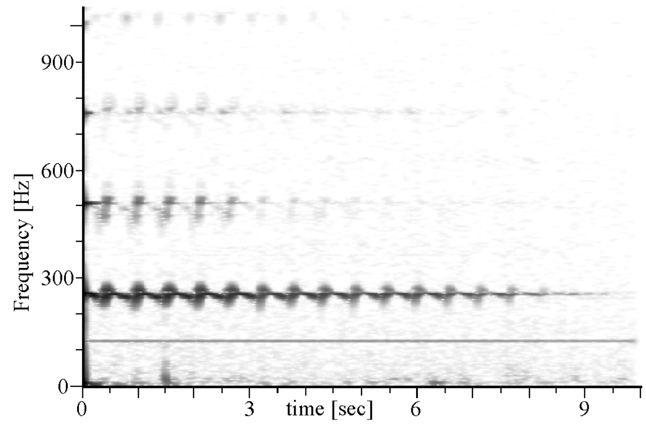

Figure 5: *Sonogram of a guitar string pluck with vibrato.*

6.4. Resonant Ring Modulation

When f_c for AM becomes large enough that a resonant frequency in a particular critical band of hearing splits by more than about $15 - 20\%$ of the band's center-frequency, the human ear perceives the resulting sound quite differently [12]. Rather than perceiving "beating" or "roughness," the ear resolves the resonant frequencies independently, which may no longer be harmonic. The standard formulation of this effect has been termed *ring modulation* [13]. However, in this case the behavior is somewhat different due to the resonant properties of the string, which cause the resulting effect to sound less inharmonic than standard ring modulation. For instance, if the relationship between f_c and f_0 is such that the string would be driven at unnatural frequencies, then these frequencies are damped considerably. On the other hand, if f_c is chosen to be related by a ratio of small integers to the fundamental frequency f_0 of the string, sets of resonant frequencies may be achieved that equivalently could be mapped to a "pseudo-fundamental" subharmonic of f_0. For these reasons, we refer to this effect as *resonant* ring modulation.

We implemented the modulation using a Max/MSP patch and a FirePOD sound interface, which introduced additional delay, but the limiter was still able to enforce marginal stability. Figure 6 shows a sonogram of the results of playing an ascending chromatic scale starting from $f_0 = 85$ Hz over one octave. The constant carrier frequency $f_c = 3 \times f_0 = 255$ Hz was chosen to be harmonically-related to f_0. While the resonant frequencies corresponding to the natural harmonic series of the string increase as the scale progresses, additional resonant frequencies decrease in pitch due to the ring modulation. In this sense, this effect shares some characteristics with foldover and aliasing.

7. SUMMARY

This paper presented a survey of various audio effects that can be physically applied to a rigidly-terminated vibrating string using feedback control techniques. Damping, AM, tremolo, sustain, FM, vibrato, and resonant ring modulation were discussed, and experimental results were presented. The ability to apply many of these

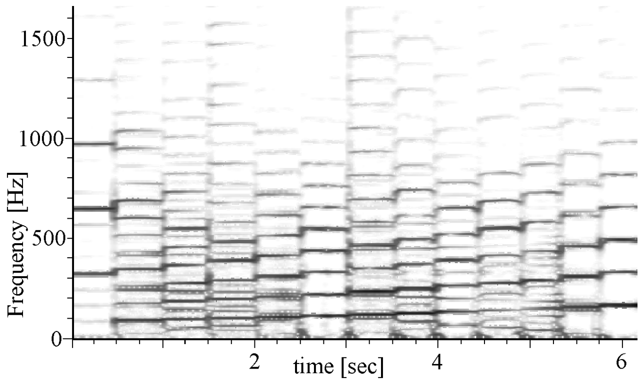

Figure 6: *Resonant ring modulated scale.*

nonlinear and/or time-varying effects relied on the placement of a dynamic range limiter in the feedback loop. The waveforms for the examples in this paper and other related examples can be found on the following website:

http://ccrma.stanford.edu/~eberdahl/Projects/PhysicalEffects/

8. ACKNOWLEDGEMENTS

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