Digital Audio Systems

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Graduate Program in Audio and Acoustics

Spatial chorus effect with fractal modulation and enhanced user functions

Assignment 1: Initial technology review

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ABSTRACT

The underlying aim of the stereo chorus effect is to emulate the combination of multiple like voices in unison and provide an extended stereo image. Like it's close cousin the flanger, whose job is to '*confuse the ear's time-correlation mechanism*'[1], it also uses a system whereby a signal is added to a dynamically delayed exact replica of itself. One important distinguishing factor between the two effects however lie in the way the delay line duration is modulated. For a chorus effect to attempt to recreate the realism and tiny discrepancies of a multi-layered ensemble, the modulation must be generally faster and *random*. Chorus effects in general give the user little control over both the modulation signal and the spatial aspects inherent in chorusing. In this paper I will be discussing a new design for a 'spatial' chorus effect that incorporates a modulation signal derived from a fractal algorithm with low-pass filter control, and the implementation of extensive user controls and parameters that center around the de-correlation of left/right signal paths resulting in a spatially *enhanced* outcome.

1. INTRODUCTION

The effect known as 'chorusing' has been omni-present in modern music production since the discovery of delay based effects many decades ago. Born from the hallowed process requiring two analog tapes machines, chorus is a derivative from members of the same family, the *flanger* and *vibrato*.[2] It has an ability to add a shimmering glow to a sound as well as spatial width or adding general size to a source. In particular the chorus effect has had an impact on guitar sounds being one of the most commonly used FX pedals. However it's not only relegated to that area, it's been known to be used on almost any instrument if the situation calls for it. As an example, The Police 'Walking in the moon' has chorusing most evident on the guitar, less evident but equally noticeable on the bass and high hat, and lastly *may* be evident (though it sure sounds like it) on the reverb return of the vocal! To get an appreciation for the type of effect chorusing produces, please listen to the example [wotm_1.wav].[3] A 'stereo' chorus inherently adds more spatial width due to the variances in pitch and frequency spectrum it provides as a result of the process. This has made chorusing one of the most useful tools in audio production enabling essentially mono sources a stereo transformation. Due to the random nature of the modulation, the outcome is far more pleasing and functional than other more rudimentary and static exercises in faux stereo imaging.[4][5]

Considering that a chorus effect uses a randomly modulated delay-line [6] usually controlled by white noise, the notion of a fractal based modulating signal therefore brings initial speculation as to whether or not it would serve the purpose better than white noise. Fractal patterns exist in an enormous range of processes within the framework of nature and it could be argued that an investigation into this phenomenon in relation to uses in audio processing is warranted.

The other area that is of key interest here is the introduction of extensive functions and parameters dedicated to expand user control over important aspects of the chorusing process. Standard user controls are normally relegated to two simple concepts of *speed* and *width* (which will be discussing in great detail later), however the design proposed and implemented in this paper offer far greater user control over many more aspects of the chorusing function. In particular, the independent manipulation of left and right signals in general for *spatial enhancement* is of prime concern. In this way, the de-correlation of what is heard at each ear provides significant improvements in stereo imaging and spatial effect. The manipulation of the modulation signal and it's function also provide a powerful tool in shaping the *sound* of the chorus. This greater control I believe will make the chorus effect an even more useful tool for audio production.

A 'spatial chorus' effect incorporating fractal modulation has been constructed in MatLab for the purpose of experimentation and evaluation, including parameters associated with a far higher level of control for testing than if it were to be implemented as a commercial plug-in. This hopefully will give an insight into the defining of a set of user controls that will provide a comprehensive and practical application. This aim of this paper is to review and discuss all aspects of the new design and relevant theories. The next stage will include testing processed audio samples with a group of subjects, who will then discriminate over the usable parameter settings and overall effectiveness of the design at a later date.

It is necessary at this point to clarify some **terminology** that will be used. This chorus effect is being designed for audio personnel and enthusiasts so it is prudent to speak in terms of the chorus *user controls* that will be presented on the face panel (GUI) to avoid any confusion. The non-modulated signal will at most times be referred to as the 'dry signal' and the delay modulated signal will be the 'wet signal' which is the way these are normally referred to in terms of an FX *send and return* in standard audio production practices. It's also economical in regards to written expression. Other user controlled processes and functions will be addressed as they arise.

1.1 Delay based effects

DBEs belong to a very popular family of digital audio effects that revolve around the occurrence of comb filtering when you add and delay two identical signals, and pitch variance from a dynamic delay time. In the former, a series of peaks and troughs appear at regular intervals dependent on the length of the delay between the two signals. [*Figure 1]* If the delay time were to move *dynamically*, this 'comb' would move up and down the spectral scale creating a 'hollow' sweeping sound commonly called a *filter sweep.*[7]

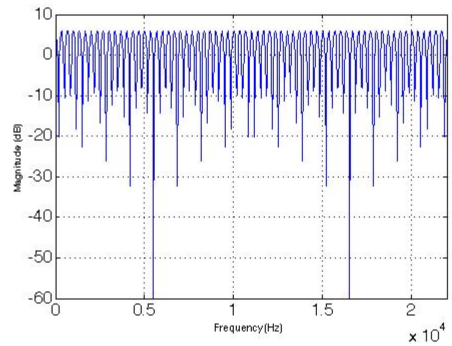


Figure 1. A graphical representation of a comb filter effect using a 1kHz tone with a delay line of 3ms.

Frequencies that double – peaks (full cycle): t = seconds

$$1/t \,,\, 2/t \,,\, 3/t \;\rightarrow \infty$$

Frequencies that cancel – notches (half cycle):

$$\frac{1/2}{t} \,,\, \frac{3/2}{t} \,,\, \frac{5/2}{t} \;\rightarrow \infty$$

However, one member of the family, the *vibrato*, relies only on the delay modulation, resulting in a pitch variance that is similar to the *doppler* effect. This is achieved by modulating the delay time with no 'feed forward'. In other words, no replica of itself to create a comb filter. The pitch goes down as the sound *moves away* and up at it *moves closer*. [8]

All delay-based effects have one thing in common though which is a modulating delay. Each effect has it's own range of values that work efficiently to achieve it's own *distinctive* sound, whether it be pitch variance, comb filtering or a combination of the two. [9]

Effect	Range (in milliseconds)
Vibrato	0 - 5
Flange	0 - 10
Chorus	1 - 30
Doubling	10 - 100
Echo	50 -

Figure 2. The range of delay times that help define the sonic characteristics of DEB effects..

The amount of the deviation from the base delay is often called the *depth,* referring to the amplitude (or depth) of the modulation. This is a very common parameter in

DBE's that can lead to extreme sounding results: a *Martian* effect with a chorus, or an enhanced filter sweep with a flanger. Flangers tend to favor a larger amplitude of modulation to accentuate the filter sweep *effect*, it's main feature. Chorus on the other hand moves more toward very small modulation changes to create a more *diffused* filtering and pitch variance. It is quite common for both effects to incorporate a 'feed back' signal and subsequent gain structure (flangers in particular), which will either increase the intensity of the effect or *blur* it further. [9] The more sustained the note is, the more that the effect is notable as the modulation has time to fully act on the ear's time correlation mechanism.

There are varying types of modulation used to dynamically control the delay time of a DBE. A flanger uses a slow sinusoidal shape in the sub audio range (typically 1-9Hz) [10] in comparison to a chorus which uses a random configuration moving much more shallow and generally faster. It's this modulation *type* that gives each effect it's own signature sound and place in audio production. The random nature of white noise commonly used as a chorus modulator serves the purpose of enabling very small, rapid and random changes in the frequency structure of a sound. This is said to emulate the not so perfect choral affect of many similar sound sources in unison. The prospect of using a fractal-based modulation is interesting, as it will modulate in a different pattern to white noise. This will hopefully achieve a dynamic movement more akin to what happens in the rest of nature, and it's own form of *beautiful chaos* [11]. [12] [13][14]

1.3 Implementation of a fractal modulator

Fractals are a pseudo-random 'pattern' found in physics and have been described as the 'finger print of nature' [15]. Benoit Mandelbrot first coined the term *fractal* in the first published paper on fractal geometry and it was soon discovered that it is '*unparalleled at measuring and modeling the world of natural phenomena*'. [16] A fractal is an object or quantity that displays self-similarity and does not need to exhibit precisely the same structure at all scales but the same *type* of structures must appear on all scales. An example of this is the shape and structure of coastlines. As you zoom in or out on a particular part of a coastline, the same type of shape should appear self-similar, meaning if you were to magnify a section of the set, the whole set starts again. Fractal design is particularly useful when describing the properties of many natural objects and processes, from the shape of snowflakes to the pathways of the capillaries in your body. [17] Jackson Pollock was an example of Fractal Expressionism whereby rather than mimicking nature he simply '*adopted it's language*' [18] in his drip paintings.

There are another group of fractals known as stochastic random fractals which '*contain a random or statistical element*', and it is this group that is of main interest here in this investigation. These fractals '*are not exactly self-similar, but rather statistically self-similar. Each small part of a random fractal has the same statistical properties as the whole*'. [18] As Gianpaolo Evangelista explains in his 2006 paper 'Fractal Modulation effects' for the 2006 DAFx conference, '*These signals with a pseudo-random behavior can prove interesting as control functions of audio effects such as phaser, flanger, chorus, vibrato, e.g., by replacing the traditional LFO with a fractal LFO*'. [20] Which leads us to the implementation of a fractal based modulating signal for this chorus design.

A 64-sample fractal algorithm was implemented to create a stochastic, statistically self-similar pseudo-random noise signal to modulate the delay-line of the chorus effect. Seven sets containing random numbers, each one double the size of the previous between 1 and 64 are then randomized, which can be described by $a = 1/f$. An example of this process is outlined in [*Figure 3]* showing a smaller 8-sample (three set) fractal algorithm, which can be expanded to accommodate any size of repeating random number sets.

$$x_1 = [\mathbf{a_{11}, a_{12}, a_{13}, a_{14}, a_{15}, a_{16}, a_{17}, a_{18}}]$$
$$x_2 = [\mathbf{a_{11}, a_{12}, a_{13}, a_{14}}]$$
$$x_3 = [\mathbf{a_{11}, a_{12}}]$$

$$x_{Conc} = \begin{bmatrix} \mathbf{x_1} \\ \mathbf{x_2\ x_2} \\ \mathbf{x_3\ x_3\ x_3\ x_3} \end{bmatrix}$$

$$x_{frac} = [\mathbf{a_{11}, a_{12}, a_{13}, a_{14}, a_{15}, a_{16}, a_{17}, a_{18}}]$$

(where the a_{ij} entry is the sum of the $a_1 - n$ rows of x_{Conc})

Figure 3. An example of an 8-sample fractal algorithm when each entry is a random number. The function can be expanded to accommodate any size of repeating random number sets. A 64-sample fractal system was implemented for the chorus design utilising seven sets,

each one double the size of the previous between 1 and 64.

2. CHORUS DESIGN AND USER CONTROLS

The chorus design is based on a series of extended parameters that ultimately would lead to a definitive set of **user controls**. These would give the user enhanced control over standard attributes such as *speed* and *depth* as well as incorporating those for 'spatially enhancing' the reproduced sound. With most functions, independent controls for the left and right signals (delay, depth and modulation signals) are present which provides further means of de-correlation and perceived 'stereo width'.

It is intended that this chorus design will eventually be implemented as a plug-in for digital audio workstations (DAWs) commonly used in audio production. [*Figure 4]* shows the basic signal flow of the design. In this particular design there is no feedback signal present for the initial purpose of evaluation, however this may be introduced later once the priorities of the design are evaluated.

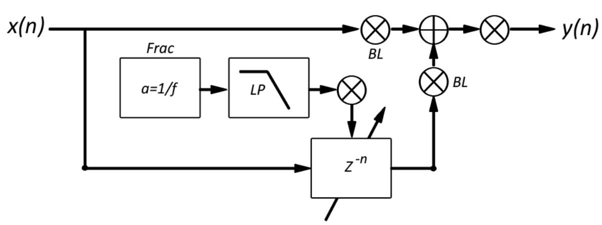
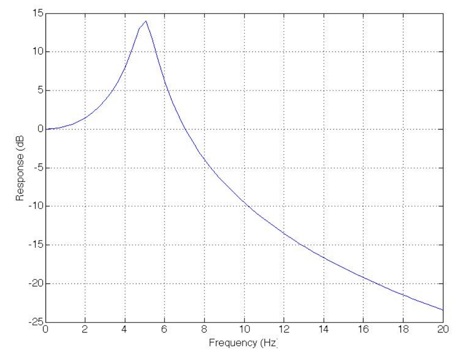


Figure 4. 'Spatial chorus with fractal modulation'

2.1. Speed

In regards to *speed* we are referring to the modulation rate of the wet signal; in user defined terms, this is how fast the modulation will occur. It is represented as cycles per second (Hz) and achieved by regulating the number of random oscillations that occur per second in the fractal modulation signal. A number of [random number] sample points is determined, which is then *resampled* to create an audio signal corresponding to the overall sample rate of x(n). To maintain and control the sub-audio rates necessary, a second order low pass filter is implemented to remove any spectral content above the desired frequency and in many ways this is crucial to the outcome. The cut-off frequency and bandwidth of the filter significantly changes the spectral content of the modulation signal, which in turn directly affects the outcome of the chorusing. If the bandwidth (Q) is wide, a resonant peak is introduced at the cut-off frequency resulting in a large peak with significantly more energy at a single frequency. [Figure 5(a)] This in turn will reduce the randomness of the modulation signal tending more towards *flanging*. Alternatively, if the Q is narrow, the randomness is retained. [Figure 5(b)][21]

(a)



(b)

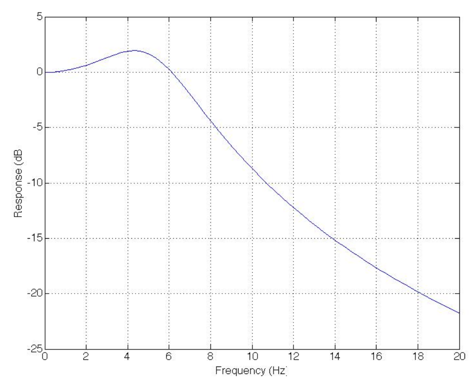


Figure 5. Due to the nature of this particular second order low-pass filter employed, (a) *if the bandwidth (Q=5) is wide a resonant peak is introduced at the cut-off frequency resulting in a large peak with significantly more energy at a single frequency. This in turn will reduce the randomness of the modulation signal tending more towards flanging. (b) Alternatively, if the bandwidth (Q=1) is narrow, the randomness is retained.*

The *user controls* concerning the modulation rate will consist of ***speed***, ***filter frequency*** and '***Q***'.

2.2. Delay

The *delay* function can be described as the delay offset of the delay-modulated signal (wet signal). When this delay is imposed, one of the fundamental elements of DBEs comes into effect, *comb filtering* (as discussed earlier) which of course is particularly relevant to flanging. The combination of the dry signal and the delayed wet signal produces a series of peaks and troughs in the frequency spectrum. However, the delay function of a chorus is more closely linked to *speed* as it is the *modulation* of the delay time that causes variances in pitch (like vibrato), and this forms the principal characteristic of chorusing.

Chorusing relies on small, rapid and random fluctuations as opposed to flanging and vibrato, hence different working parameter ranges are required to achieve it's individual sonic characteristics At small delay times between 1-2ms, changes in timbre are at their most noticeable. It could be argued that this is not a desirable outcome for a chorus effect as that is more an attribute of flanging. When delay times are above 2ms, the timbre attributes caused by the interference to the frequency spectrum become less evident and the pitch variance becomes more dominant. At delay times more than 30ms an *echo* becomes apparent which again is not desirable. [22] [23]

2.3. Depth

Commonly referred to as *depth*, the deviation from the mean delay offset of the wet signal provides the *strength of fluctuation* of the modulation. The depth is defined as a ratio to the delay offset. The maximum amount of depth is determined by the wet signal delay offset to the dry signal, hence the degree (speed) of depth (measured in μs) is dependent upon this ratio. [*Figure 6*] A delay offset of 5ms and a depth ration of 1:0.2 will result on a depth of 26.5 μs; a delay of 10ms with the same ratio will result in a depth of 52.9 μs. As the delay increases, so does the 'speed' of the depth. The question is whether this ratio captures the perceptual magnitude more accurately when processing signals of predominately low or high frequencies. The perceived fluctuation strength is noticeably more audible with signals of higher frequencies than those of lower frequencies with the same parameters used. This no doubt is attributed by the 'clear dependence of fluctuation strength on center frequency' as stated in in 'Psychoacoustics – Facts and Models' by Zwicker and Fastl [24] [25]

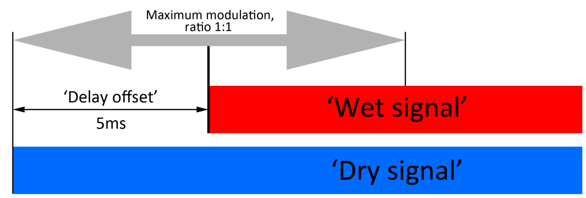


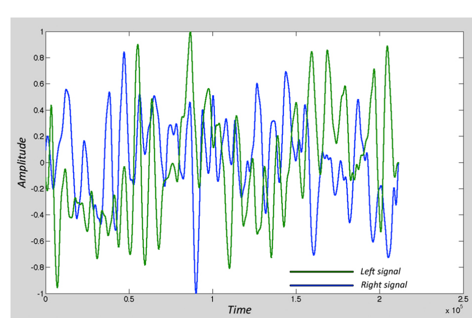
Figure 6. The maximum amount of depth is determined by the wet signal delay offset to the dry signal, hence the degree (speed) of depth (measured in µs) is dependent upon this ratio.

2.4. 'Spatial width' - Independent left/right modulation signals

A chorus effect in general can produce a result that inherently increases the spatial width of a mono signal. In many standard chorus effect designs, only two user controls are generally present being *speed* and *depth.* In the case of designs that incorporate a feedback system, a third user control *feedback,* is present to regulate the level of the feedback amplitude. In-line with an aim to create a chorus that offers more user control over additional areas, two functions that concentrate specifically on spatial attributes have been implemented into the chorus design.

The main spatial element of the chorus design is independent modulating signals for discrete left and right signal processing. With both signals modulating independently of each other, a definitive spatial *width* effect is created by separate pitch variance evident at each ear. This spatial component is obviously more pronounced with the use of headphones creating an event reminiscent of binaural effects, however it is also quite prominent through speakers. Figure 7(a) clearly demonstrates two incoherent modulating signals.

(a)



(b)

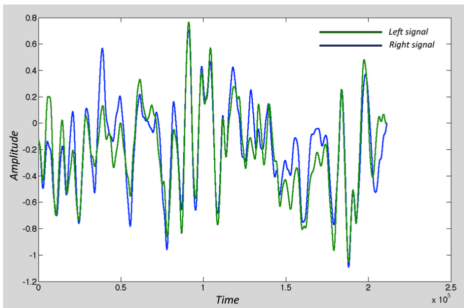


Figure 7. a) No correlation between left and right modulators, b) partial correlation (70%)

Another user control function is now introduced to compliment this process, a *mixing* system to regulate the coherence between modulation signals. [*Figure 7(b)]* illustrates a partial (70%) correlation of modulation signal. This enables the user to vary the amount of spatial width that is desirable for any particular application [*Figure 8]*. There is a noticeable difference especially listening via headphones between correlated and non-correlated modulation signals giving a powerful user control over the spatial width of the result.

We will now call this modulation mixing system in terms of a *user control* as **'Spatial width'**.

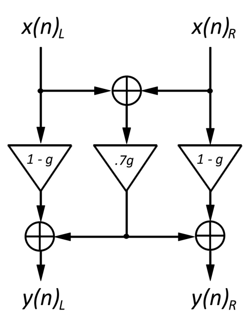


Figure 8. Controlling the amount of correlation between the independent modulator signal , a mixing system is introduced to regulate as a percentage. There is a noticeable difference especially listening via headphones between correlated and non-correlated modulation signals giving a powerful user control over the spatial width of the result.

2.5. 'Spatial movement' - Delay of dry signal to emulate Interaural Time Delay (ITD)

The inclusion of a dry signal delay is the second spatial element to this chorus design. It works in a very interesting way by enabling the user to move the dry signal in line with the *delay offset* of the wet signal. This means that the wet signal can fluctuate between leading and lagging the dry signal in the time of arrival at the ear.

We will now call this delay of the dry signal in terms of a *user control* as **'Spatial movement'**.

If for example, the dry signal is delayed by 5ms [*Figure 9]*, this spatial variation is like that associated with '*the variation in Interaural Time Delay (ITD) for a sound source taking a circular path around the head, since maximum modulation depths for ITD don't often exceed .6 to .7 ms.*' [26]

The result is prominent and effectively enhances the spatial movement of the modulation within the stereo image. *Specifically* when using headphones to monitor the result.

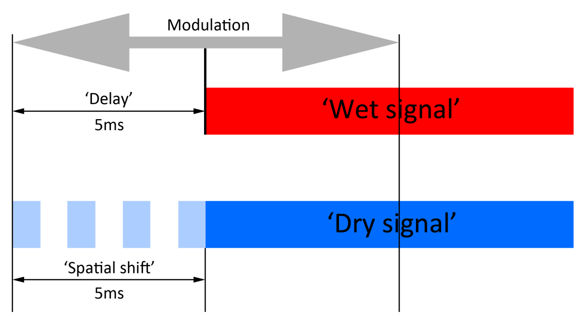


Figure 9. By delaying the dry signal at the same amount as the wet signal, the delay-modulated signal (wet signal) can fluctuate between leading and lagging the dry signal in the time of arrival at the ear. We will now call this in terms of a 'user control' as 'Spatial shift'. This spatial variation is like that associated with 'the variation in Interaural Time Delay (ITD) for a sound source taking a circular path around the head.

2.6. 'Spatial mix' - Effects send/effect return

Finally, a user control to determine how much of the chorus effect will be present in the result is implemented much like an effects send and return. This simply gives the user the ability to balance how much dry or wet signal is present in the output. It is a very common element with most digital effects and eliminates the need to have separate audio channels (effect return) to balance the two signals. However if several input signals are to be sent to the effect (effect send) the balance can be set to all wet signal and the dry signal levels can be set at the source.

We will now call this dry/wet signal mixing system in terms of a *user control* as **'Spatial mix'**.

DISCUSSION AND CONCLUSION

Chorusing has been proven over the decades to be a mainstay of the audio engineer and musician's arsenal of delay based effects, sharing both the theoretical basis of both the flanger and vibrato but with it's own identifiable sonic characteristics. The pitch and spectral variance unique to the chorus mean that it's place as a vital digital effect is assured and further development is essential to fully explore the possibilities of this stalwart of spatially centered effects. It's ability to transform mono sources and the outcomes possible begs further advancement.

The chorus effect is clearly defined by the type of delay modulation used and relevant to the interaction with pitch and frequency. The implementation of a fractal modulation signal, with it's relationship to many natural objects and processes poses many questions as to it's effectiveness as an alternative to white noise as a catalyst. Also the implementation of a filter design that seemingly regulates the randomness of the modulation is a new dimension to the way the chorusing function *behaves* with the multitude of inputs and their own sonic characteristics in terms of individual application and subsequent psychoacoustic perception.

The development of more comprehensive and extensive **user controls** not only relate to the core of standard chorusing functions but extend to more spatially concentrated elements that could be considered a primary development. The aim of this design is to give the *user* more choice of parameters and control governing a broader range of functions that have not been available previously. The spatial aspect of course has been the most important underlying aspect of this exercise, in particular the control over the correlation of parameters between elements of the left and right channels. This undoubtedly has a major impact on the psychoacoustic foundation to '*confuse the ear's time-correlation mechanism*'. The control over the independent modulation signals has proven so far to be paramount to the perceived spatial movement and apart from the search for a suitable range of usable parameters, will be a priority area in the planned subject based testing as the next stage of the project.

3. REFERENCES

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