FEEDBACK PROCESSES.

An investigation into non-linear electronic music

A dissertation submitted to Middlesex University
for the degree of MA in Sonic Arts

10th May 2002

Knut F. Aufermann

Student number: 9944738

Lansdown Centre for Electronic Arts

ELA4996 (60 credits)

Dissertation and supporting material

I declare that no portion of the work referred to in this dissertation has been submitted in support of an application for another degree of qualification of this or any other university or other institute of learning.

Acknowledgements:
Thanks to Sarah Washington, all the contributors to the ‘feedback’ issue of the *Resonance* magazine, Ed Baxter, John Wall, Andrew Deakin and John Dack.

FEEDBACK PROCESSES.
An investigation into non-linear electronic music.

Included with this dissertation are two audio CDs (practical course work) and a copy of the magazine *Resonance* Vol.9 No.2 with an accompanying CD.

1. Introduction

Over the last two years I have researched the deliberate employment of feedback processes by musicians, composers and sound artists for the most basic level of their work: sound creation. This research provides the context in which I place my personal approach to sound and my own way of making music. The dissertation in hand is dedicated to uncover the various links between theory and praxis that are embedded in working with feedback processes. It is broadly divided into two parts. In the first part I describe my technical, artistic and aesthetic development in live feedback performances. This features a combined approach where aspects of my practical experimentation are intertwined with research information about the electronic and systemic aspects of feedback. In this context the practical side was almost always the precursor, opening up the way for theoretical ideas through empirical work. This chapter is supported by two accompanying CDs of selected audio recordings made during the course period; extensive comments on these recordings can be found in appendix 3.

Chapters three and four form the second section with theoretical findings covering feedback in music and non-music related fields (chapter 3) followed by a brief excursion into philosophical and political aspects of feedback (chapter 4).

The word feedback can be used in several ways, which share a common connotation but essentially have very specific meanings. I would like to give three definitions for the word feedback:

1. The process happening in a system where a part of the output is fed back to the input of the system.
2. The signal itself that is routed from a system's output back to its input.
3. The perceivable output of a system that feeds back (especially when the system oscillates).

All three definitions will be used in the following text in such a way that the chosen meaning is obvious through the context it is placed in. To adjust the terminology and vocabulary used in the dissertation for specific meanings that occur in connection with feedback related ideas, I have defined certain words in the glossary (appendix 2). These words will be underlined in the main text body the first time they appear.

2. Personal practice - introduction

"Some of art is that you make connections between things that no one else would ever make." (Lucier, 1995: 70)

'How to make feedback?' was never the question. It is probably not wrong to say that almost everyone who produces feedback for the first time does so by accident. This is already one of the most important characteristics of feedback: it is unwanted and often unforeseeable. My first attempts at using feedback were teenage experiments with a portable cassette recorder and a microphone which resulted in recordings of two friends and myself shouting along with the screaming feedback between speaker and microphone. The cassette machine ceased to function after about 20 minutes, which probably created my initial respect of the dangerous effects that feedback can have on equipment and hearing. Electroacoustic feedback is generally considered a nuisance because of the ear splitting volume that can be produced by standard speakers and amplifiers. When I work as a live sound engineer I still fear the sudden rise of feedback that makes the audience cover their ears. Coming back to the question at the beginning, it is not 'How to make feedback?' but 'How to like feedback?'

2.1 Technical aspects

The first time I deliberately used feedback was when I tried to change the timbre of a delay of a sound. Most delay units have a so-called feedback parameter that normally controls the decay time of the delay and leaves the timbre of the repetitive tail unchanged. But when a part of the delay unit's output is routed back to its input via a pre-fader auxiliary send the sound of the delay changes gradually. Before the advances of digital delay units this effect could be created through tape loop based echo units that allowed a variable part of the signal of the playback head to be redirected to the record head. Dub reggae extensively uses this mixing technique that can be employed in the studio as well as in live performances. This notion of positive feedback as a 'gentle' effect is often overlooked, although the Chambers Dictionary of Science and Technology states clearly in the case of electroacoustic and electronic feedback:

> "feedback (*Acoustics*). Reaction of reproduced sound in an enclosure on to the microphone controlling same, resulting in change in response of the system, apparently increased reverberation, and, if excessive, actual oscillation (howling). (*Telecommunications*) Transfer of some output energy of an amplifier to its input, so as to modify its characteristics." (Chambers Dictionary of Science and Technology, 1974: 446)

I would like to clarify the various aspects of positive and negative feedback that can exist in and between electronic music equipment, including my own set-up, by using the classification given in diagram 1 (see below). In general there are two variables that determine what kind of feedback can occur in such a system: the phase relationship between input and feedback signal and the relative amount of feedback signal[1]. The dotted lines do not show a linear border between the quadrants but rather indicate vague crossover areas between positive and negative feedback processes that can either be input or system dependent.

[1] I have omitted a mathematical description of feedback in electronic circuits in favour of a phenomenological approach. A short and informative article on the mathematics of feedback in electronics can be found in the McGraw-Hill Encyclopedia of Science & Technology (1997, vol.7: 37-39)

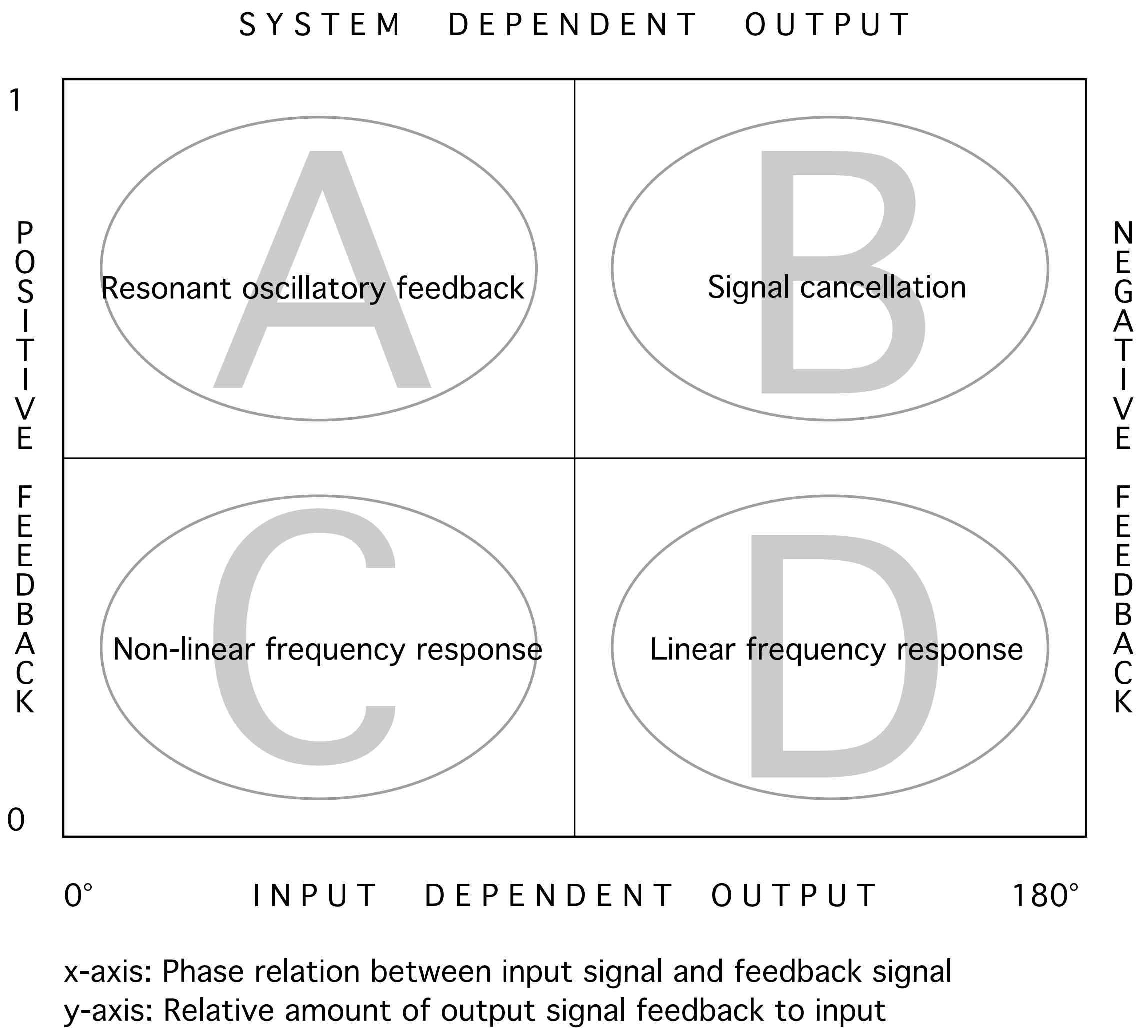


Diagram 1: Possible feedback systems

2.1.1. Negative feedback

Quadrant D represents an example of the common use of negative feedback in amplifier technology to achieve linear frequency responses by "(...) reducing gain of an amplifier by feeding part of output signal back to input out of phase with incoming signal. Gives more uniform performance, greater stability, and reduced distortion." (Chambers Dictionary of Science and Technology, 1974: 793)

Even without in-depth knowledge of electronics it is easy to see that when the frequency response of a system is controlled through negative feedback, its attractor state will be a linear frequency response. Any extra gain on a frequency is immediately counteracted by continuous attenuation through the phase reversed feedback signal until the system returns to unity level.

When this negative feedback happens on the level of the audio waveform it can lead to signal cancellation. **Quadrant B** shows the scenario that depends on near phase reversal and high relative level of the feedback signal.
I have experimented with signal cancellation by using the two signals with opposite phase, available at the balanced output of professional audio equipment, as individual signals for feedback loops. Practically this is easily achieved by using a XLR to two mono jack adapter, whereby the two jack tips carry the hot (XLR pin 2) and the cold (XLR pin 3) signal respectively. A phase reversal in the feedback loop makes the occurrence of “howling” feedback less likely, which is one of the reasons why a phase button is a standard feature on many live sound mixing desks. In my electronic feedback set-up a 180° phase reverse in the loop results in needing a big gain increase before audible feedback happens. The timbre of the feedback tends to be extremely harsh due to the very narrow frequency ranges that are not completely cancelled out and therefore allow resonance. My current set-up (see under 2.1.3.) does not include any balanced audio equipment.

2.1.2. Positive feedback

All sounds I produce when I perform live under the TΩN name are created by positive feedback loops between my audio equipment[2].
The above mentioned use of positive feedback to create a dub reggae style delay is an example represented by **quadrant C.** The coherence of input signal phase and feedback signal phase means that the overall output signal is

[2] There are also important negative feedback functions or so-called nonlinearities involved that control the upper threshold of my output signals (see 2.1.3 Equipment set-up).

boosted according to wave theory. Slight frequency dependent phase differences are introduced due to the characteristics of the delay unit (digital, analogue or tape based), and any other effects such as equalisation inserted in the feedback loop. These are responsible for the filter effect that changes the timbre of the delay. Altogether, the output signal is still very much determined by the input signal into the system, although the change of timbre displays a non-linear characteristic of the system's frequency response. The connection between feedback, reverb, delay and phase is examined in-depth based on a case study later on (see 2.1.4.).

Quadrant A shows the form of feedback that I am most interested in. It is not input dependent, its occurrence is only determined by the characteristics of the system that produces it. When the amount of in-phase feedback signal from the output to the input reaches a critical threshold the system starts to oscillate. The only input needed to set off this resonant feedback is a minimal undefined noise that is inherent in any analogue electronic component and circuitry[3]. In its simplest form a circuit could for example consist of a capacitor, a coil and a necessary resistance in series that oscillate in phase between maximum and minimum capacitance (electric charge) and inductance (electromotive force) at a frequency that is defined by the values of the components and which displays a minimum impedance[4] (which I call the 'attractor state').

I will stop at this point to delve deeper into the electronic realm of feedback circuitry. Even though I constantly learn more about it, I am quite happy to let a certain scientific mystery remain; a mystery that can be explored through experimentation[5].

---

[3] In fact this noise is also existent in any part of a computer or any other digital device and only the quantization rules for their operation make sure that they are perceived as 'noise free'.

[4] For information on the various types of electronic oscillators see McGraw-Hill Encyclopedia of Science & Technology (1997, vol.12: 615-621)

[5] For the last year I have experimented with the electronic circuits of small devices (children's toys, cassette recorders etc.), trying to find new connections between components to establish new local feedback loops. I am not going to write more extensively on circuit bending as it is worth a separate essay. A good example of the sound world of cicuit bending is Xentos' *By the time you get this it will be dud [Symphony of Unstruments]* (Resonance 9.2, CD track 10).

2.1.3. Equipment set-up

Given that none of the devices I use for making feedback music are actually designed for it they create an astonishingly interesting output. I have not yet found a piece of audio equipment that could not be used to produce electronic feedback when placed in a loop.

With every new idea about feedback I check my set-up for the possibility of new connections or the integration of another device. My current set-up includes four independent feedback loops each with individual output volume controls shown in diagram 2 below. Almost all loops can be combined in a linear fashion or they can form a new loop containing all the elements of the source loops.

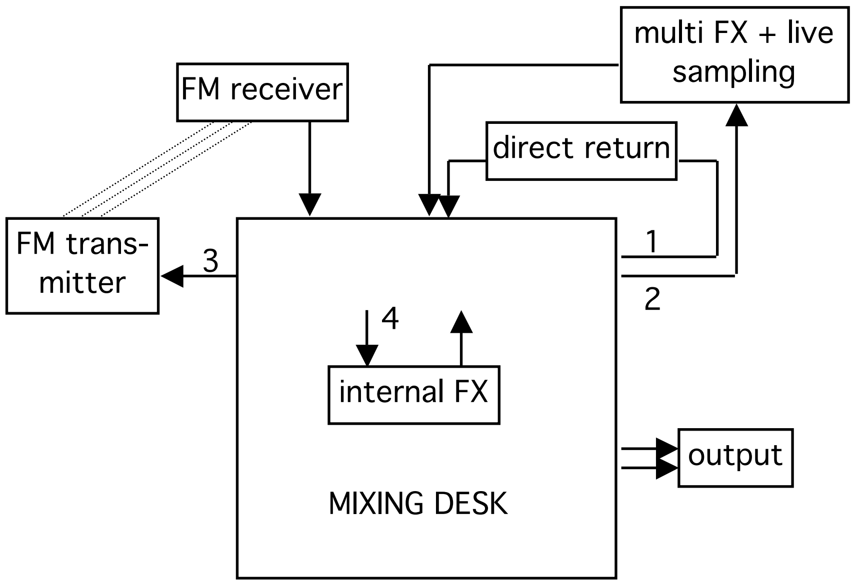


Diagram 2: TΩN set-up showing four feedback loops

Loop 1 is a simple return from an output of the mixer (ETEK AD1223) back into an input. The signals achieved through feedback on this path are generally very high in level due to the lack of a limiting device and often clip the internal circuitry. The built in EQ of the mixing desk offers a very volatile control possibility of the produced frequency, which can cover the whole frequency spectrum up to inaudible ultrasonics. Due to their strength these very high

frequencies often bleed through potentiometers and are noticeable in the mix and other loops even when the respective channel fader is shut.
Loop 2 consists of a string of three digital effect units (Korg AX30G, Korg Kaoss Pad, Lexicon JamMan) that cover the whole range of standard effects available. Two of the units (Kaoss Pad, JamMan) have live sampling options which means that they can record and playback several seconds of their input with the possibility of variable sample rate playback. The quality of the equipment ranges from 12bit/32kHz guitar effects (AX 30G) to decent 16bit/48kHz analogue to digital conversion rates (Kaoss Pad), whereby the lowest sampling rate determines the highest frequency at which the loop can feed back. When ultrasonic frequencies from loop 1 are introduced into this loop alias frequencies of the otherwise inaudible signals are produced. One effect unit (AX 30G) generally compresses the signal to avoid digital distortion. This loop is the most versatile in terms of timbre of the produced sounds, and the live sampling option gives it important rhythmical flexibility.
Loop 3 consists of a low power FM radio transmitter (Velleman K1771 FM oscillator) and a pocket radio receiver (Sony 10F - TR40) to produce radio feedback. The modulation and demodulation[6] (tuning) processes involved in this loop allow interesting sound transformations that can be controlled by the tuning of the radio or hand resistance on the aerials of the transmitter or receiver. I often use radio feedback in conjunction with loop 2, combining them in a single, more complex feedback loop with two input and output points.
Loop 4 utilises the pre-set reverb and delay variations of the built-in effects unit (ETEK EFX2000) of the mixing desk. Assisted by the routing possibilities of the mixer this function, that was designed as a post-fader auxiliary send, can be sent back to its input to create rich spectral sounds. The particular timbre and

[6] Tuning into a radio station involves feedback circuitry. The high frequency oscillator in the receiver can be controlled by changing the resistance in its positive feedback loop so that it resonates with the carrier frequency of the incoming radio signal (87.5 - 108 MHz for frequency modulated radio signals) which allows the extraction of the modulated sound information. Analogous to this is the way the theremin works, where the resistance of the hand introduced through the antenna determines the frequency of the internal oscillator.

character that digital feedback develops when it is part of a feedback loop is explored in the next section (2.1.4.).

When I come across new audio equipment my first thoughts are: Can it feed back? How will it sound when placed in a feedback loop? Unfortunately these questions are of no concern for the manufacturers[7] and so I have to discover the answers through trial and error when I try to incorporate a new piece of equipment into my set-up.

2.1.4. Digital reverb (case study with sonograms)

There is an inherent connection between reverb, delay, phase and feedback in electronic music. As early as 1959 Karlheinz Stockhausen was not only using feedback to modify tape delays in *Kontakte* (1959-60) but also used feedback loops on reverb units[8] (see Ernst, 1977: 44-47). A decade later the deployment of feedback to create delays and timbre changes was common practice, documented for example in chapter 10: Reverberation, Echo and Feedback of the book *Electronic Music* by Allen Strange (Strange, 1972: 86-96). Another decade further on the advance of digital technology has provided an answer for the need of artificial reverberation and here again feedback loops play an important role.

My reason for looking into the function of digital reverb was to find out how a system decides on what frequency (or frequencies) to feed back when the loop is first established. In other words, what are the attractors of the system? Equalisation has already been identified as a strong tool to shift attractors, for

---

[7] The only manufacturer I have come across that has made provisions for the control of a feedback loop is Moog. Their latest analogue delay unit offers the possibility to patch any external effect unit into the signal path that carries the feedback signal of the delay in order to change its sound (see http://www.gaspedal.com/moog.htm , see also sections 2.1. and 2.1.4.).

[8] Listening to *Kontakte* it became obvious that Stockhausen did not only use feedback loops to change the sound colour of tape delays and reverberation but also used electronic feedback as a sound source. The score for *Kontakte* reveals that he created feedback oscillations through maximum settings on amplifiers that have a gain control based on positive feedback. He calls the resulting sound 'similar to a sine wave' ("(...) fast wie ein Sinuston klingt." (Stockhausen, 1968: 68)). It might be similar but it is immediately recognisable as feedback.

example in loop 1 of my set-up (see 2.1.3.). But also time-based effects such as reverb can act as a filter (comb filter, see diagram 3) and therefore influence the frequency response of a system.

> "Every filter uses phase shifts to alter signals. A filter phase shifts a signal (by delaying its input for a short time) and then combines the phase-shifted version with the original signal to create frequency-dependent phase cancellation effects that alter the spectrum of the original." (Roads, 1996: 18-19)

Reverb is basically created through a short delay with a feedback loop from the combined output of original and delayed signal to its input (see Currington, 1995: 5). "If the delay time is set between 10 and 50 ms, an echo results, with shorter fixed delays, a comb filter response results (...)"[9](Pohlmann, 2000: 631).

This model for reverb is obviously simplified. "The processing program in a reverberation unit corresponds to a series and parallel combination of many such feedback systems (for example, 20 or more). Recursive configurations are often used." (Pohlmann, 2000: 633)

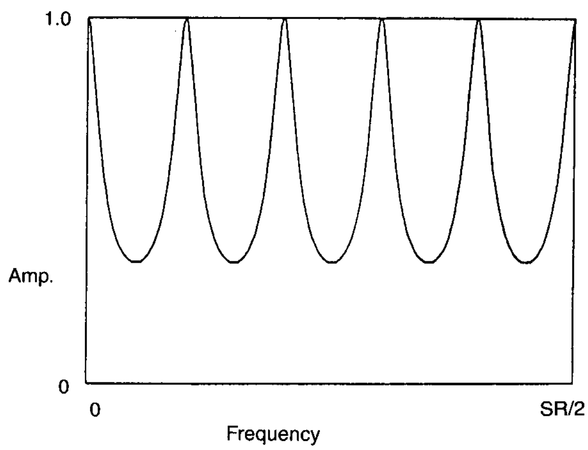


Diagram 3: Frequency spectrum of a recursive comb filter (taken from Roads, 1996: 417)

[9] This is an example of a dualism in our perception of sound. A delay can either be heard as a filter or an echo depending on the delay time. Natural reverb thus always colours sounds.

To find out if these inherent filter effects of digital reverb units have an influence on the feedback frequencies of my set-up, I examined the very beginning of the recording of my piece TΩN k4.0v (track 2, Resonance 9.2 CD) with the help of high resolution sonograms using the computer program AudioSculpt. The track starts with the opening of a feedback loop, which incorporates two reverb units (Korg AX30G, Roland SRV-3030). Sonogram 1 shows the development of the four strongest attractors at 3.2kHz, 6.4 kHz, 9.6 kHz and 250Hz during the initial 35 milliseconds. The first three frequencies are obviously harmonically related with the strong fundamental at 3.2kHz and could be seen as a product of the above mentioned comb filter effect. The frequency of 250 Hz albeit has to indicate a non-related attractor which after its initial appearance loses amplitude (sonogram 2) only to return with its own harmonics as the single point of attraction after about 7 seconds into the track, when a slight amount of equalisation perturbed the system in favour of the lower frequencies.
It was possible to zoom into the lower frequency region of the sonograms (0 - 800Hz) to analyse further energy patterns that evolved around the main feedback frequency of 250 Hz at the start of the track (sonogram 3). During the first 30 ms there are fan-shaped side bands developing that show the distinct characteristic of a comb filtered signal at about 33 ms into the track which is a result of the applied reverb algorithm. Sonogram 4 however shows that there are more complex filter patterns evolving in the first 110 ms of the track where the comb filter becomes a periodic phenomenon (circa every 30 ms) that is also a function of frequency. This developing heterogeneity in time and frequency of the filter points is obvious in sonogram 5, which also reveals a periodicity in amplitude of the main feedback frequency of about 200 ms (5Hz modulation).
Altogether these sonograms make it very clear that feedback sounds are a far more complex meshwork of frequencies than their sound would indicate, on the other hand this might be the explanation for their unmistakable sonic quality.

2.1.5. Process sounds

Feedback often seems instantaneous. Opening the feedback loop on my mixing desk produces a sound, functioning almost like a conventional, linear, electronic instrument. It is important to remember that every time a feedback loop is established, a cyclical system-dependent tuning process starts and constantly continues that determines all characteristics of the output.

As an analogy for such a system's behaviour with a stable output I would like to employ the following example: take a pocket calculator, enter the number 1000 and then press the square root button (√). If you continue to press √ you will, after a certain number of cycles, end up with a stable output of 1, which is the attractor of the system. This output of 1 is system dependent not input dependent, it does not matter what number you put into the calculator initially, the continuous process of taking the square root will after some time always 'tune in' to the unchanging output of 1.

When working with feedback this tuning process of settling on a stable output can happen in an extremely short time, so that it becomes hard to detect. For me Alvin Lucier's composition *I am sitting in a room* (Lucier, 1995: 322, 324) reflects an attempt to make this feedback process, the crossing of the line from quadrant C to quadrant A in diagram 1, audible. He is only interested in the process of bringing out the resonant characteristics of the room[10] using speech[11] as the initial input, like a primer for the crystallisation of the resonant frequencies. The modus operandi, the cycle of recording the delayed playback of a previous recording (see Lucier, 1995: 322, 324), makes sure that some

---

[10] Lucier was well aware of the fact that not only the room but all components of the set-up (like in a feedback loop) would influence the sound. "The signal goes through the air again and again; it's not processed entirely electronically, it's also processed acoustically." (Lucier, 1995: 96) "Make versions in which, for each generation, the microphone is moved to different parts of the room or rooms." (Lucier, 1995: 324)

[11] Lucier's choice of speech as the input was made for purely acoustical reasons. "(...) I decided to use speech; it's common to just about everybody and is a marvellous sound source. It has a reasonable frequency spectrum, noise, stops and starts, different dynamic levels, complex shapes. It's ideal for testing the resonant characteristics of a space because it puts so much in all at one time." (Lucier, 1995: 98) " (...) I don't want what goes into the space to be too poetic. I want it to be plain so that the space becomes audible without distractions(...)." (Lucier, 1995: 100)

stages of the tuning process (that ends with fairly stable resonances of the strongest room modes) are captured on tape. Just as in the example with the calculator, it is not possible to trace back what the original starting point of the recordings was.

"Make versions that can be performed in real time." (Lucier, 1995: 324)
When I first read this last sentence of the score for *I am sitting in a room* it felt like a permission (with hindsight) for two recordings I made last year. Because I am working with electronic feedback I wanted to create an experiment[12] that shows the development of resonant tuning inside a reverb unit with the help of a delay. The set-up for this experiment is shown in diagram 3.

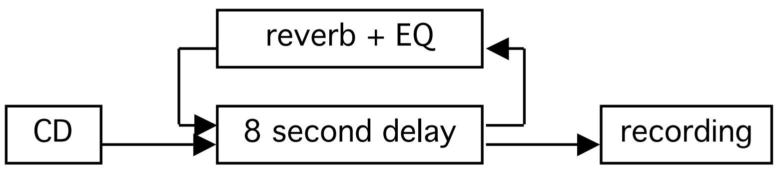


Diagram 4: Set-up for process experiment

The delay unit (Lexicon JamMan) was set up so that it would keep every input signal for 8 seconds before it would play it out as a single echo. To start the experiment I played 8 seconds of music into the delay unit which then played it out while at the same time recording the return signal coming through the reverb unit and so effectively stringing together all the subsequent cycles that passed through the loop. By trial and error it was possible to find gain settings that allowed the system to run without any interference from the outside[13], after the initial sample of music had been played in. The reverb unit (Roland SRV-3030) was set to a short reverb time (0.4 s, 5% wet mix) and an EQ boost (+12dB at 560Hz, 5% wet mix) which formed the attractor of the system. To

[12] I started this experiment from a completely different view-point (see chapter 3 for further discussion) and only later discovered the analogy to Lucier's composition.
[13] In technical terms: the amplification factor equals the damping factor (see McGraw-Hill Encyclopedia of Science & Technology,1997, vol.12: 618)

prove that the output of the system is independent from the input (given enough cycles), I arbitrarily chose two different excerpts of music that were subjected to the process. The results can be heard on track 3+4 on the accompanying CD 2.
The sole purpose of this experiment is to act as a reminder that feedback sounds are the result of a continuous process which can be interfered with by changing its supporting system.

2.2. Musicality

Performing live with feedback is like open-heart surgery. Luckily the patient consists of cables and boxes with faders, buttons, rotary pots and LEDs, and any breakdown of the system's ability to beat/oscillate/feed back causes only minor embarrassment. One aspect of the performance could be described as maintenance, in general actions that keep the system, which I will call an 'instrument'[14] from now on, within acceptable boundaries. These actions are loops of negative feedback between myself and the instrument to avoid high output levels resulting in unintentional distortion or low feedback levels leading to unwanted silences. These functions undoubtedly profit from a certain amount of experience, a better maintenance technique allows for longer uninterrupted playing time. It is similar to learning how to cycle: it gets interesting when you manage to stay on the bike for a reasonable amount of time. After that comes the decision of which path to cycle or, regarding musical performance, which path to play on the instrument. In both cases my motto is: never the same route as before.
This decision to continuously perturb the musical output to create new sounds is made much easier by the non-linear behaviour of the instrument.

[14] I am not going to enter the discussion about what constitutes a musical instrument. My feedback set-up produces sound and therefore is my instrument.

2.2.1. Non-linearity

The transition time between sounds, the time an attractor needs to take effect is highly variable and can range from a few milliseconds to several seconds. Contrary to other electronic instruments, which have linear portamento characteristics, the speed of sound transitions in my feedback instrument is a function of the way it is played. To explain this I have to borrow the idea of <u>bifurcation</u> points from the science of thermodynamics. At these points of instability the instrument is forced to change its behaviour to accommodate the changes in the system's environment brought out by the player. These changes in the environment can be small (for example a touch of equalisation) or drastic (for instance the insertion of a new effect into the feedback loop) and can have different effects on the actual behaviour and on the output of the instrument. Again there is no necessarily linear correlation between the changes the player makes and the resulting sound.

To give an example, let's assume that the instrument produces a stable high frequency sound. When I now want to shift this sound towards a lower frequency I might try to boost the low frequencies by equalisation. One possible reaction may be that the sound does not change until the LF boost reaches 10 dB and at +10.1 dB the sound immediately changes to a lower frequency. Another possibility is that a boost of only 0.5 dB sets off a development that over several seconds cross fades the high frequency into a lower one.

2.2.2. The role of time

One parameter that influences the reaction time of the instrument is what I would like to call the 'internal time' of the respective feedback loop. Feedback can be considered as a continuous cycle of analysis and synthesis; the synthesised output of a system is analysed and fed back to the input to inform the next synthesis step. Physics Nobel prize winner Gerd Binnig has suggested that these cycles should be the basis for the measurement of time: “Ein Zyklus des Synthese-Analyse-Rädchens ist eine Zeiteinheit.”[15] (Binnig, 1992:119) Given the varied characteristics of the feedback loops in my instrument they have different, sometimes variable internal times which depend on electronic component values, AD and DA conversion latencies and delay effect settings which range from microseconds to seconds. The stability of a loop is roughly proportional to the speed of its internal time; the faster the time the easier the system will act on perturbations and so change its output and vice versa. These observations stem from my playing of the instrument but will be supported by other research detailed below (see 3.2. Stability and chaos, see also 3.4. Perception and communication).

2.2.3. Aesthetics

Most of the music I play is completely improvised, I do not have any musical background or training in composition. This allows me to speak of feedback music outside the conventional music terminology and analysis. I think of my music as ‘sounds in process’ or ‘process sounds’ that need all the attention when they are played, so preconceptions about what might happen and when are obstructive. I agree with Toshimaru Nakamura when he writes:

> “You can’t be a feedback improviser when you have your brains filled with your big beautiful pictures prior to your performance. If you show up to the venue like that, you won’t have any fun.” (Nakamura, 2002: 5)

The nature of my instrument teaches me to expect everything and nothing. Since I have been working with feedback I have started to think of sound as waves on every level, for which a different vocabulary is needed. Phase, frequency, resonance, amplitude, filter, pulse, modulation and tuning are words, which I can use to describe my sound work adequately. A conventional term like pitch cannot be translated into frequency, it simply does not apply to my music; timbre or colour of a sound is at best expressed in sonograms. Whenever

[15] My translation is: “One cycle of the small synthesis-analysis-wheel is a time unit.”

I resort to using conventional music vocabulary it is to highlight analogies, or because my own language has not developed fully yet.

One of my main reasons for playing music is, just as I imagine for most other people, is to evoke emotions. The sounds can be beautiful, angry, powerful, sad, etc., generally they have to produce a 'gut reaction'. The knowledge of the internal structure of my instrument and the way it produces sound as described in the chapters above is very important to me. It does not only inform my way of playing but makes me aware of the fact that there is no hierarchy between instrument and player, a fact that has also been noted by several contributors to the (enclosed) 'feedback' issue of the magazine *Resonance* (see Nakamura, Myers, Prime, Pentos Fray Bentos, Rogalsky & Aufermann (all 2002) in *Resonance* Vol.9 No.2).

This relationship between musician and instrument is another form of feedback, which I have so far only hinted at and treated as a matter of course. Having given an alternative vocabulary to describe the sounds of my feedback instrument I would also like to describe the way of playing it with a different terminology that is mostly borrowed from biological systems research: Playing feedback is chasing attractors. I try to bring out new attractors by pushing the system towards a bifurcation point. To be able to foresee at least the proximity of these points of instability and change I have to listen intensively, almost analytically to the output of my instrument to hear the rise of new colourations in the sound which are usually heralds of more drastic changes. Other interventions, for example the insertion of new components into the feedback loop obviously bring immediate effects.

My activity whilst playing can be defined as the function of a catalyst. It is only possible for me to bring out sounds that the instrument is already capable of producing. Confirmation to this idea comes from Matt Rogalsky when he writes about David Tudor's feedback instruments:

> "The electronic devices, though human-made, are following their 'natural' tendencies; the performer's role in creating the piece is to herd the electrons in one direction or another." (Rogalsky, 2002: 9, 10)

2.3. Performance

One of the fascinating characteristics of concerts of improvised music is that as a member of the audience it is easy to get involved in a feedback loop with the performers. The music is an offering to the audience and not a show, it encourages communication rather than consumption. Daniel Charles describes this coupling between audience and performers as the climax of a performance, which lets them experience collective time (see Charles, 1989, 80 - 82), the internal time of their feedback loop. I have experienced this connection many times, both as a member of the audience and as a performer.

If a group of artists perform together another level of feedback coupling can occur that locks them in a state of mutual understanding, in phase, synchronising their intuitions, allowing resonances. It is beyond the scope of this dissertation to further examine this inter-personal feedback, but I would like to mention four projects of mine that are based on it.

One is my duo with the extraordinary saxophonist Lol Coxhill in which I process his playing and thereby establish a very audible feedback connection between our two instruments[16]. A live recording of this duo is included on the CDs that accompany this dissertation (track 1 on CD 2, see appendix 3 for comments). As with all improvised music it is impossible to capture the full extent of the performance on a recording.

The second project is a duo with Berlin based painter Marcus Heesch in which case the more abstract connection between live music and live tempera painting[17] was made concrete by gluing two contact microphones onto the canvas so that they pick up painting noises. The microphones remain as part of the painting (see appendix 3) and will later act as speakers to play back the recording of the music and painting session in a future exhibition. An extract of

[16] Phil Durrant's article in the feedback issue of Resonance (Durrant, 2002: 11) illustrates in more detail his experience of a very similar duo combination with saxophonist John Butcher.

[17] A documentation of Marcus Heesch's collaborations can be found at http://www.artpartout.de/live-tempera/art-list.html .

the recording is included on the accompanying dissertation CD 2 (track 2, see also appendix 3).

Two long-standing groups I am involved are the all electronic quartet Responge and The London Improvisers Orchestra[18]. Responge (with Sarah Washington, Anselm Caminada and Borre Molstad) is a good example for the validity of improvisation with electronic instruments. The character and musical understanding of the group continuously develops although all members frequently change their instrument set-ups. The traditional idea of sticking to one instrument in order to master it is proven obsolete.

Being a member of the London Improvisers orchestra gives me the opportunity to compose as well as to prove that feedback electronics can fit very well into an almost exclusively acoustic orchestral context. I do not use headphones, which means that the work in a large ensemble demands very intensive listening to detect my sounds coming from the PA system before they become too loud.[19] Although the performances vary with the size of the orchestra, quite often remarkable musical resonances emerge during the improvisations.

3. Feedback analogies

“ (...) if you make an analogy between two things, you’re not only saying that one of them resembles the other, you’re saying that the identity of one is concealed in the other. It’s as if all things are the same, but have different outward appearances, and the transformation from one to another is an active process in which truth is determined, but you’re at different values along the way.” (Lucier, 1995: 132)

This part of the dissertation opens up a view about feedback manifestations outside of my personal world of sound production. A wider scope of feedback processes is introduced and discussed in order to find analogies between these

---

[18] Documented on two double CDs (*the hearing continues...*, Emanem 4203, *freedom of the city 2001 - large groups*, Emanem 4206).

[19] I frequently get comments from members of the orchestra that I am a quiet electronics player but I am convinced that part of my sounds stay unnoticed because of their integral or alien characteristics.

processes and to extract their common features. My hypothesis is that all feedback processes have a similar structure and follow the same rules.
I will start with feedback examples connected with music and then move on to other disciplines.

3.1. Musical instruments

Most musical instruments rely on perceptual feedback whilst playing to achieve the desired response. Fretless string instruments for instance, violin, cello and double bass or other less conventional instruments like the musical saw, slide guitar or the theremin need a fine tuning regarding their pitch which can only be applied by the player after the initial tone has been played. This loop between perception (listening to the instrument) and motor activity (adjusting the hands or fingers in this case) of a player is a type of negative feedback similar to that used for error correction in electronic appliances: comparing the system's output to a reference and adjusting it accordingly. Highly skilled musicians have almost eliminated the need for this adjustment by perfecting their motor activity routines through practice. These routines essentially only make sense if the instrument displays linear characteristics.
Acoustic instruments generally consist of a non-linear exciter and a linear resonator, which can be coupled in a feedback loop, similar to that between musician and instrument. To illustrate this network I have combined two approaches into a single diagram depicted below.
Most parts of the diagram, except the italics are copied from a figure in Tristram Cary's Dictionary of Musical Technology that illustrates the "(...) action of playing an acoustic instrument" (Cary, 1992: 20). He states: "With some instruments (e.g. bowed strings, wind), the performer is in a real time feedback loop because the note is controllable throughout." (Cary, 1992: 20)
The italics inside the dotted rectangle in the diagram are taken from a "model of instrumental oscillation" (Roads, 1996: 280) by McIntyre, Schumacher, and

Woodhouse (MSW) for their digital sound synthesis model of woodwind instruments.

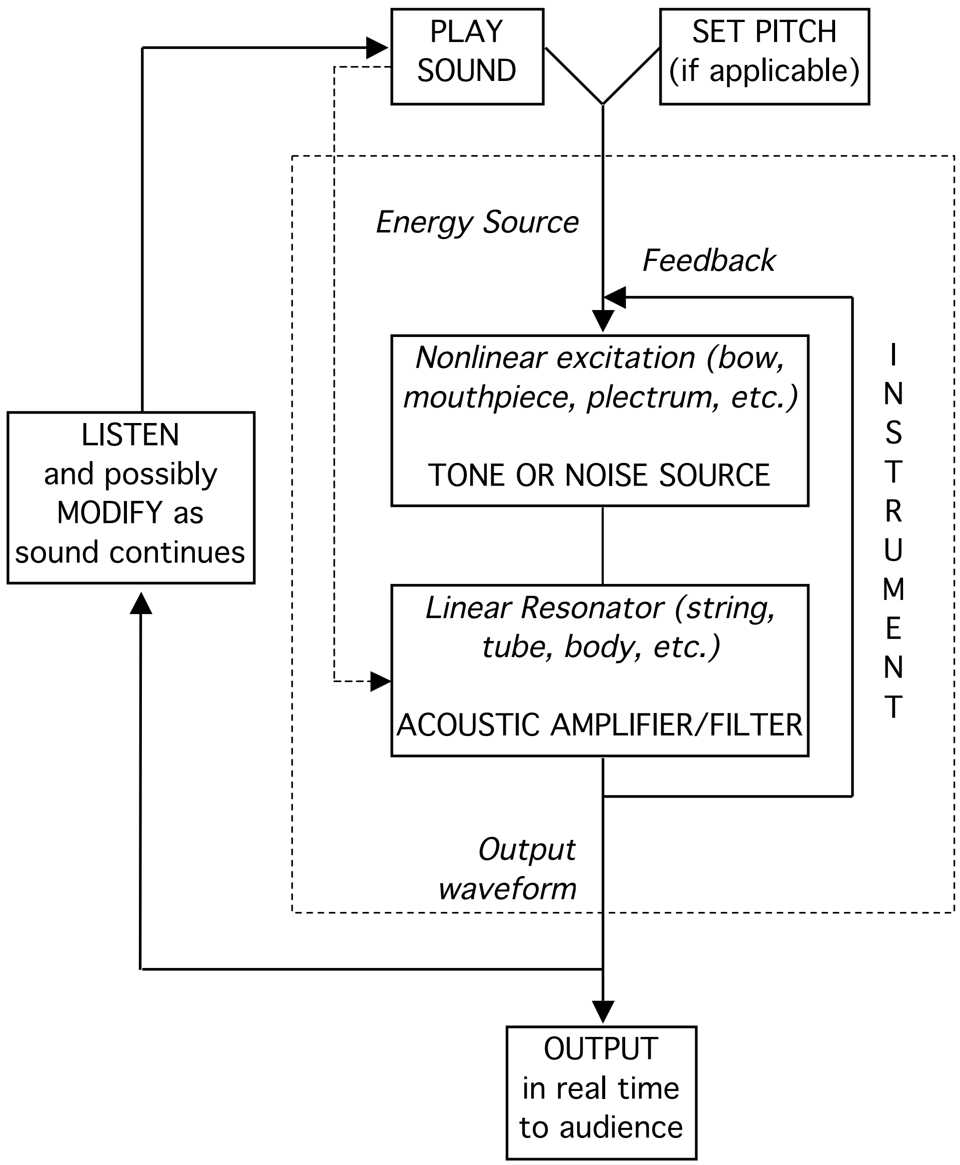


Diagram 5: Instrument models

The MSW model highlights the fact that in the case of the saxophone for instance, it is not only a question of the player controlling the instrument but also the instrument controlling the player by allowing only certain tones to resonate[20]. Depending on the fingering there are standing waves of certain frequencies possible in the tube of the saxophone. Any excitation of the reed by blowing into the mouthpiece thus has to include the possibility of finding one of these frequencies otherwise no tone will develop.

Experienced saxophonists hear the tone they are about to play beforehand in their mind and thus pre-empt the instrument's response in a kind of feed forward[21] that prepares their lips for finding the desired excitation point of the reed.

Finding analogies between the model for oscillation in acoustic instruments (see diagram 4) and electronic feedback instruments is not difficult. Here the source of energy is an electric potential, the non-linear excitation is achieved through positive feedback feeding on white noise inherent to the components, which allows for all possible frequencies to develop, and the linear resonance is determined by component values (analogue) and algorithms (digital) of the feedback loop.

The interesting difference between acoustic (or conventional electronic) instruments and feedback instruments is that feedback instruments allow much more variations and control[22] of the resonance, as component values and algorithms can be continuously changed by the player with an option of merging or splitting multiple feedback loops. Maybe like playing a liquid violin in zero gravity, being able to form its body whilst playing, or playing two violins at the same time and then fusing them into one only to then separate them into three violins.

[20] This fact explains why it is difficult for first timers to get any sound out of a saxophone, whereas it is easy to produce sounds on instruments that do not have a built-in feedback process between player and instrument e.g. a piano.

[21] The notion of feed forward processes is discussed extensively in the book *Destiny and Control in Human Systems* by Charles Muses (Muses, 1985)

[22] This control is expressed through the dotted arrow in diagram 4. In the original diagram of Cary the arrow expressed the option that in "some instruments (e.g. French horn) the player can also modify the resonating system while playing (hand in bell) (...)."(Cary, 1992: 20, 21)

Even without these extended options of modifying the resonance of feedback instruments the traditional notion of linearity given to resonance can be challenged in the electronic realm.

3.2. Stability and chaos

White noise in systemic terminology represents chaos, which is inherent in every electronic instrument. An important step away from the traditional idea of musical instruments being perfectly controllable is to give rise to these chaotic forces of noise through electronics. This means the deliberate encouragement of non-linear behaviour as it is done when playing feedback electronics.

It is for cultural reasons that chaotic instruments have not emerged in the shops, given that there are simple electronic circuits known that show chaotic behaviour. One well-documented circuit is the Chua oscillator. "This circuit provides a paradigm for the study of chaos due to its universal chaotic properties, its simple circuit design, its ease of construction, and its rich variety of over 40 attractors." (Bargar: 3)

The output of Chua's circuit falls into the audible range and so offers the chance to study a system that is capable of stable (tone) and chaotic (noise) oscillations and all possibilities in between.

> "Signals from chaotic systems can be described in terms of stability and instability, patterns and their degrees of intermittency, transient qualities, and ambiguity of certain states. Some chaotic signals are similar to those of natural sounds; thus transient behaviours of some chaotic signals are already familiar as listening experiences." (Barger: 1, 2)

In Chua's circuit there exists an immensely interesting sound source that has been discovered recently only after thousands of years of culturally formed misapprehension of chaos has been overcome. Unfortunately the traditional ideas of music are still too strong to prevent the appreciation of truly chaotic behaviour and further research was conducted to make Chua's circuit into some sort of slightly out of tune synthesizer.

> "A challenging task consists in an efficient mapping between the space of physical parameters of the circuit (values for resistances, capacitances, inductances etc.) to the space of musical perception (timbre, pitch, etc.). (...)
> A major problem in musical applications of the Chua oscillator is the predictable and reproducible transition between attractors corresponding to different parameters. Because of the complex nature of the parameter and state space, one cannot assume that a simple change to a new parameter configuration will induce a transition to the desired new attractor. In many cases the attractor to which the system will evolve will depend on its history. Thus it would be necessary to prescribe a specific path in parameter space leading from one attractor to the next. In doing so, it is also essential that the rate at which the parameters are changed are sufficiently quasi-adiabatic such that during the transitions no accidental excursion occurs into basins of attractions of unwanted attractors like the notorious LLC [Large Limit Cycle, a ubiquitous attractor state described by the authors as acoustically especially unpleasant. K. A.]." (Mayer-Kress, Choi, Bargar, 1994)

I have included this whole quote because in my view the terminology used is perfectly adequate to describe a non-linear electronic instrument for experimental music. I am disturbed by the direction of research that wants to tame the chaotic characteristics of the circuit in order to generate "bassoon-like sounds" (Mayer-Kress, Choi, Bargar, 1994).

One of the tools found to 'trivialise' the circuit is to slow down its internal time by subjecting it to a delay[23] (see 2.2.2. The role of time).

> "A different type of control strategy has been used to stabilize unstable periodic solutions close to a chaotic attractor. The basic idea is that the difference between a signal x(t) and the time-delayed signal x(t-T) is used as a negative feedback control force (...). It vanishes for periodic solutions of the period T. In the context of musical sounds this method has a similar effect as coupling a noisy sound source to a resonator: resonating modes will be amplified and others will be surpressed. The result is a pure tone."[24] (Mayer-Kress, Choi, Bargar, 1994)

[23] The notion that delays (or bottlenecks) can lead to stability is present in other disciplines, e.g. urban development research (see De Landa, 1997: 41).

[24] This concept is discussed in more detail above (see 3.1. Musical instruments).

Because Chua's circuit offers all possibilities, from harmonic (sine wave) to chaotic (white noise) oscillation I hope that it will become the central sound processor in a future electronic music instrument.

3.3. Cell biology

Periodic oscillation that is neither simplistic nor totally random but somewhere in between, governed by a set of positive and negative feedback processes, is not an exclusive phenomenon of human-made electronic circuitry; it can be found everywhere in the organic (and inorganic) world.[25]

There are two examples taken from the world of cell biology that I want to present here, in order to show that feedback processes are at the centre of the fundamental building blocks of life. They are the cell dynamics connected to the conveyance of information (DNA) and energy (glycotic cycle) in living systems. Chemistry Nobel prize laureate Ilja Prigogine writes on this subject:

> "The basic mechanism through which molecular biology explains the transmission and exploitation of genetic information is itself a feedback loop, a 'nonlinear' mechanism. Desoxyribonucleic acid (DNA), which contains in sequential form all the information required for the synthesis of the various basic proteins needed in cell building and functioning, participates in a sequence of reactions during which this information is translated into the form of different protein sequences. Among the proteins synthesized, some enzymes exert a feedback action that activates or controls not only the different transformation stages but also the autocatalytic mechanism of DNA replication, by which genetic information is copied at the same rate as the cells multiply." (Prigogine & Stengers, 1985: 154)

The terminology used by scientists is slightly different but the analogy to all other feedback processes discussed so far is obvious. The output of a system has decisive influence on the input of the system by forming a feedback loop: in this case the DNA produces enzymes that in turn facilitate the reproduction of

---

[25] Gerd Binnig states that there is no real system that, given long enough time, would not display chaotic behaviour (see Binnig, 1992: 176). Many examples for complex oscillations are given by James Gleick in his book *Chaos - die Ordnung des Universums* (Gleick, 1988). See also my article 'Feedback is everywhere' (Aufermann, 2002: 14,15).

the DNA. ‘Autocatalysis’ in this context means positive feedback, negative feedback is called ‘autoinhibition’ and more complex variations of feedback loops are termed ‘crosscatalytic’. The following quotation on biological oscillation shares more sonic vocabulary.

> “The best understood example of metabolic oscillation is that which occurs in the glycotic cycle, which is a phenomenon of the greatest importance for the energetics in living cells (...). It consists in the degradation of one molecule of glucose and the overall production of two molecules of ATP by means of a linear sequence of enzyme-catalysed reactions. It is the cooperative effects involved in the enzyme activity that lead to the catalytic effects responsible for the oscillations. It is quite remarkable that oscillations in the concentrations of all metabolytes of the chain are observed for certain rates of glycotic substrate injection. Even more remarkable is the fact that all glycotic intermediates oscillate with the same period but with different phases.” (Prigogine, 1980: 122)
> “Glycolytic oscillation produces a modulation of all the cell’s energy processes which are dependant on ATP concentration and therefore indirectly on numerous other metabolic chains.” (Prigogine & Stengers, 1985: 155)

It is not surprising that the glycotic cycle, like many other biological cycles shows periodic characteristics. The name already states that it is cyclical, recursive, driven by feedback reactions; and in certain circumstances it reaches phase coupling[26], it ‘tunes’ itself.

The Chilean neuro-biologists Humberto Maturana and Francisco Varela call this tuning ‘structural coupling’ and say it gives the system a degree of autonomy (see Maturana, Varela, 1987: 85-100). They state that the notion of structural coupling is not only a matter of molecular biology but can also be transferred onto the (human) nervous systems and our perception.

[26] Phase coupling can be found in many areas connected to feedback processes, from the locking of radio circuits to a transmitter signal to synchronisations between earth and moon (see Gleick, 1988: 406,407)

3.4. Perception and communication

To support the idea that our perception is a result of a complex network of feedback processes I want to quote from John Annett's book *Feedback and human behaviour* where he describes the outcome of experiments on human perception:

> "In a variety of tasks subjects performed simple reaching and pointing movements before, during and after wearing prismatic lenses which displaced the visual field to one side. After wearing these lenses the subjects' pointing errors showed evidence of compensation, that is displacement of movement in the direction opposite to the displacement induced by the prism, but this only occurred when subjects had seen the results of self-produced movement whilst wearing lenses. In one experimental task, subjects were either allowed to walk about wearing prisms or were wheeled about on a trolley over similar routes for similar times. Subjects who moved voluntarily achieved full adaptation after several hours but the subjects who had been passively wheeled about did not. In short, adaptation to displacements of the visual field depends on the reception of feedback from self-produced movement. The equivalent stimulation from passive movement is not, of course, feedback since it does not depend on any output, so these demonstrations show the importance of feedback as such to the process of adaptation." (Annett, 1969: 19)

Annett also describes experiments with delaying the internal feedback time of human senses.

> "The subject wore padded earphones which excluded external sounds and spoke into a microphone. His voice was recorded on a tape recorder and played back using a second playback head displaced slightly from the recording head, so that he heard his own speech only after a short delay. With a delay of as little as half a second, speech production was affected. (...)
> Delays of either auditory or visual feedback (...) appear to be the most disruptive of all, and there is little or no adaptation even with prolonged practice. (...) any lag in the system will impose a limitation on performance which cannot be overcome unless some way is found of reducing the lag or of predicting future feedback." (Annett, 1969: 19, 20)

These examples of experiments with distorted or delayed sensory feedback show that human perception does rely on a network of internal communication that needs to be coherent[27] in information and phase. This coherence is specified by the internal structure of the internal communication system and not by the surrounding environment.

Given that the internal working of our body and senses is dependent on feedback, it is not surprising that our external communication needs feedback too. Talking to a person that pretends not to listen or to be extremely uninterested is a standard role play exercise for communication psychology students. It is immediately obvious that some sensory feedback from the communication partner is needed to be able to speak to them.

> "Feedback enables the speaker to adjust his or her performance to the needs and responses of an audience. Good speakers are generally sensitive to feedback; pompous, domineering bores manage to filter out feedback almost entirely." (Fiske, 1990, 22)

The quotation above is probably also true for musicians.

I hope that the analogies between all the different manifestations of feedback have become obvious even when I have omitted a detailed explanation of all contextual connections. It seems reasonable to me to talk of feedback processes as a universal concept whereby the same laws can be applied to completely different systems. Thus the analogies become homologies (see Ivanovas, 2002: 2).

4. Feedback Philosophy

The concept of circularity was introduced into Western mainstream culture with the advent of cybernetics in the 1940s, which makes it a recent development. When it became obvious that the implications arising from it nurtured non-linear, non-hierarchical, trans-computational ideas it was soon marginalised into

[27] An example where incoherence of sensory input can lead to sickness is when people work in an-echoic chambers and their visual feedback tells them that they are indoors but their ears state, due to the lack of reverb, that they must be in the open field. A solution to this problem is to work in complete darkness.

a pseudo-esoteric scientific niche (unless the research results could be harnessed for military purposes). In the 1970s chaos theory became the public face and fashion for non-linear mathematics and everybody had heard about the ‘butterfly effect’. The residue of this ground-breaking development is now available as Mandelbrot screen savers for computers. The capitalist Western society cannot deal with the values and doubts that grow out of feedback philosophy. What if suddenly the world turns out to be much stronger interconnected to divide it into wrong and right? What if causal thinking turns out to be only appropriate for a marginal amount of decisions? What if it turns out that so-called scientific truth is merely based on low-level statistics?

It seems that it is now up to artists to rediscover and further develop the ideas that have emerged from cybernetics. Unlike other scientific disciplines it is not necessary to be an expert (it might even be hindrance) to be able to grasp the concepts based on circularity.

The idea of feedback can be understood without knowing the details. As Alvin Lucier points out the task is to make/find connections that have not been made/found before. What better concept to work with than feedback? Feedback processes can be found in almost any aspect of life and there is a huge amount of possible homologies ready to be discovered in artistic work.

I can only agree with Francisco Varela in his closing words of an article on circularity:

> “We should do better to fully accept the notoriously different and more difficult situation of existing in a world where no one in particular can have a claim to better understanding in a universal sense. This is indeed interesting: that the empirical world of the living and the logic of self-reference, that the whole of the natural history of circularity should tell us that ethics - tolerance and pluralism, detachments from our own perceptions and values to allow for those of others - is the very foundation of knowledge, and also its final point. At this point, actions are clearer than words.” (Varela, 1985: 308, 309)

5. Conclusion

Working with feedback has had a profound influence on the way I think about music. Very early on it became obvious that there was more to feedback than just using it as an effect, it could be an instrument in its own right.

Feedback provides a solution to many of the problems I have encountered in (electronic) music:

- It allows detachment from the restrictions of conventional music theory, whilst retaining unmistakable sonic properties. The importance in the sound of electronic instruments is character (quality) not choice (quantity).
- Musicians can perform live on feedback instruments that give real-time access to all sound shaping parameters.
- There is no need to master the instrument because the player’s function is that of a catalyst and not executive.

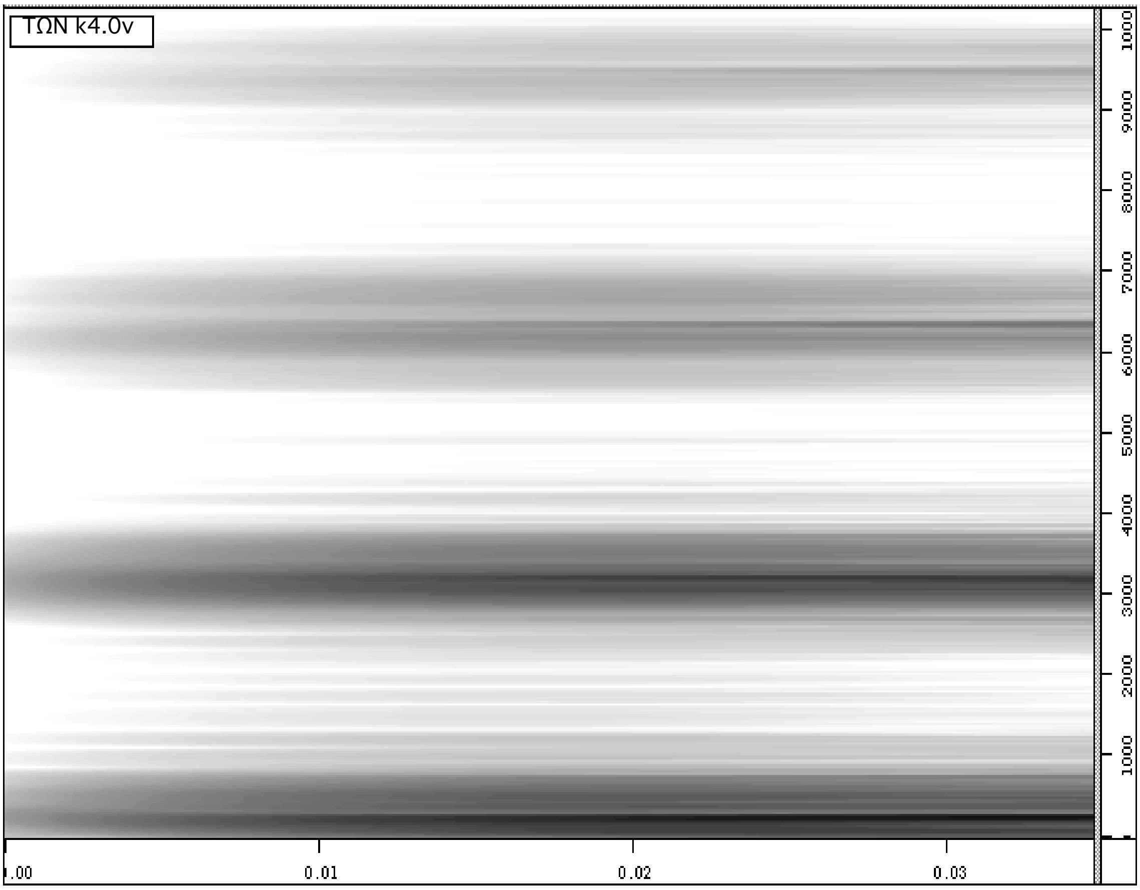
I am glad that I had the opportunity to edit the current issue (Vol.9 No.2) of *Resonance* magazine, for which I chose feedback as the central theme. It provided me with the opportunity to contact internationally acclaimed artists who work with feedback and ask them for their thoughts on the subject. Interestingly none of them declined my offer; feedback as a concept turned out to be a central issue to the work of many of the artists. The CD that accompanies the *Resonance* magazine is a unique collection of mostly exclusive feedback music. (I do not know of any other compilation on the same theme, which in hindsight is astonishing.)

This dissertation and my practical work provide an introduction to my ideas about non-linearity and circularity – two key aspects of feedback processes – and their implication for my musical work. The analogies (or homologies) I have given are personal points of reference and show the context of this work.

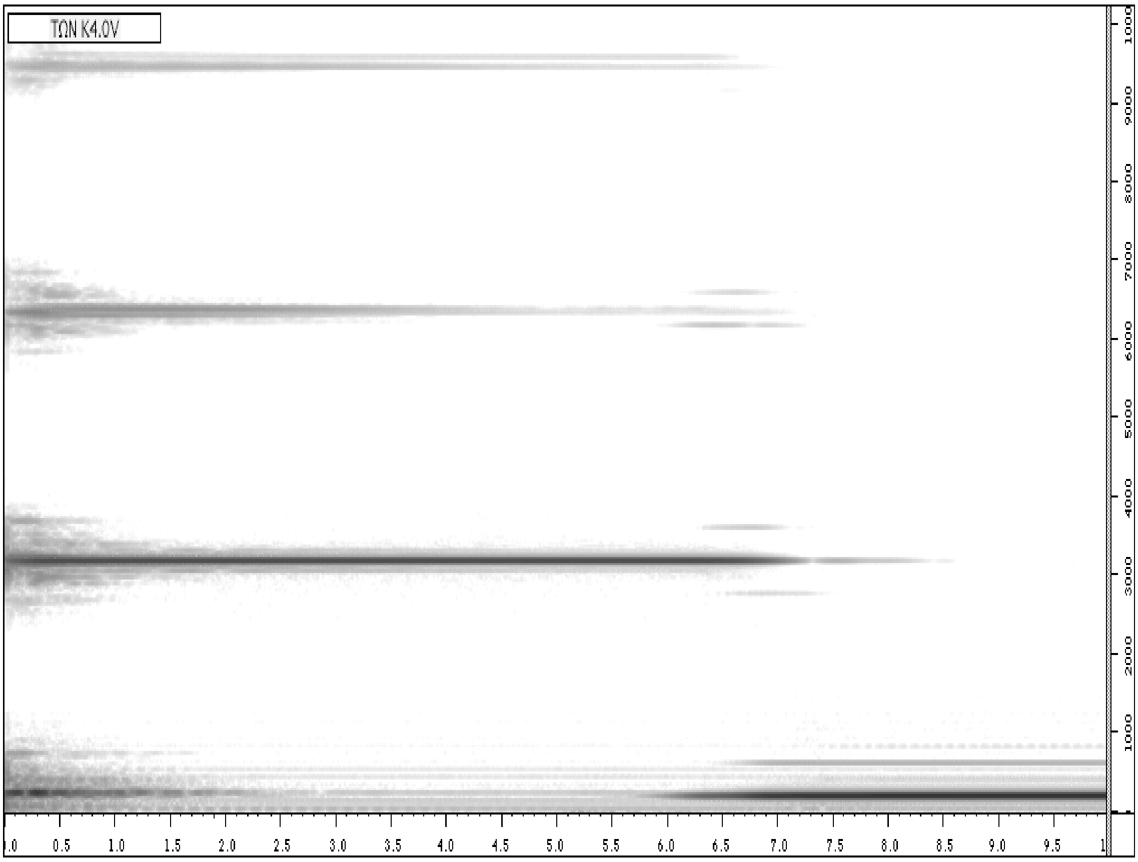
I hope that the relevance and importance of feedback processes in music has become clear and I am looking forward to future possibilities to extend this research.

Appendix 1 - Sonograms

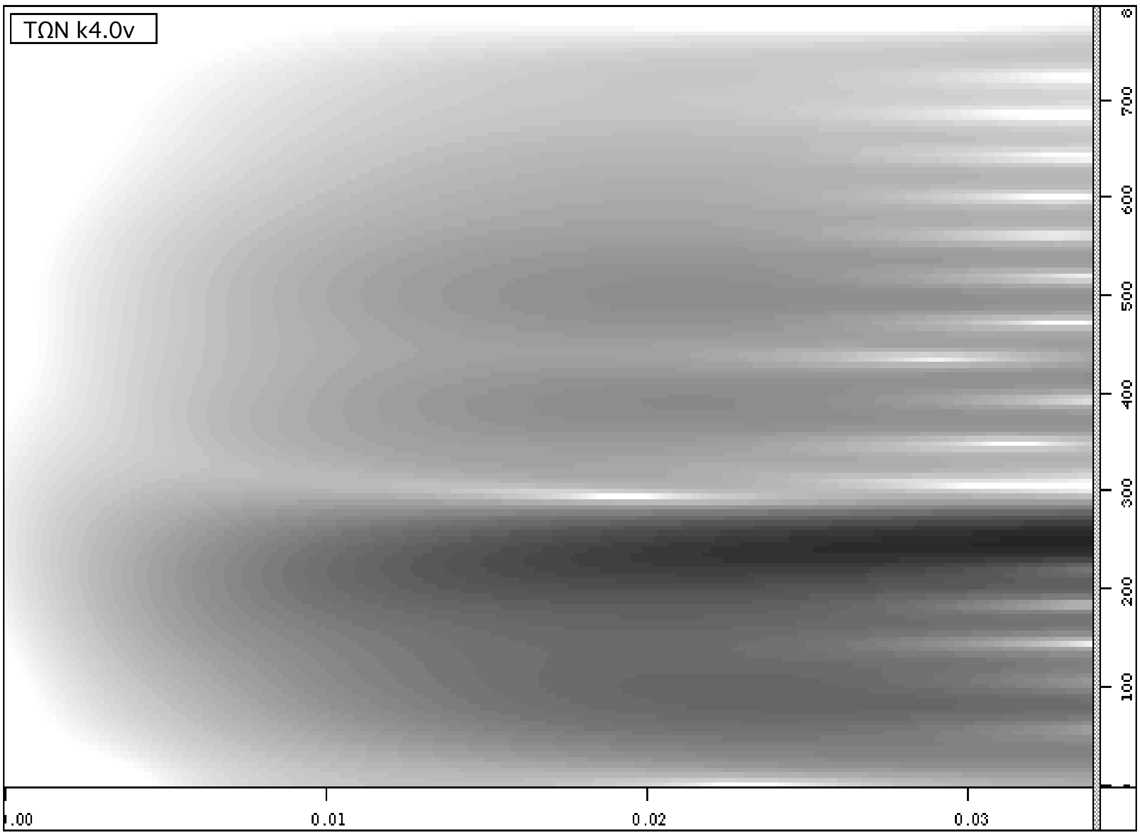
The sonograms shown have been created with the program AudioSculpt using FFT sizes between 8192 and 32768 and window sizes between 2 and 1024. The horizontal axis shows time (seconds), the vertical axis shows the frequency (Hz, linear) and the shading shows the amplitude (dynamic range approx. 60 dB).



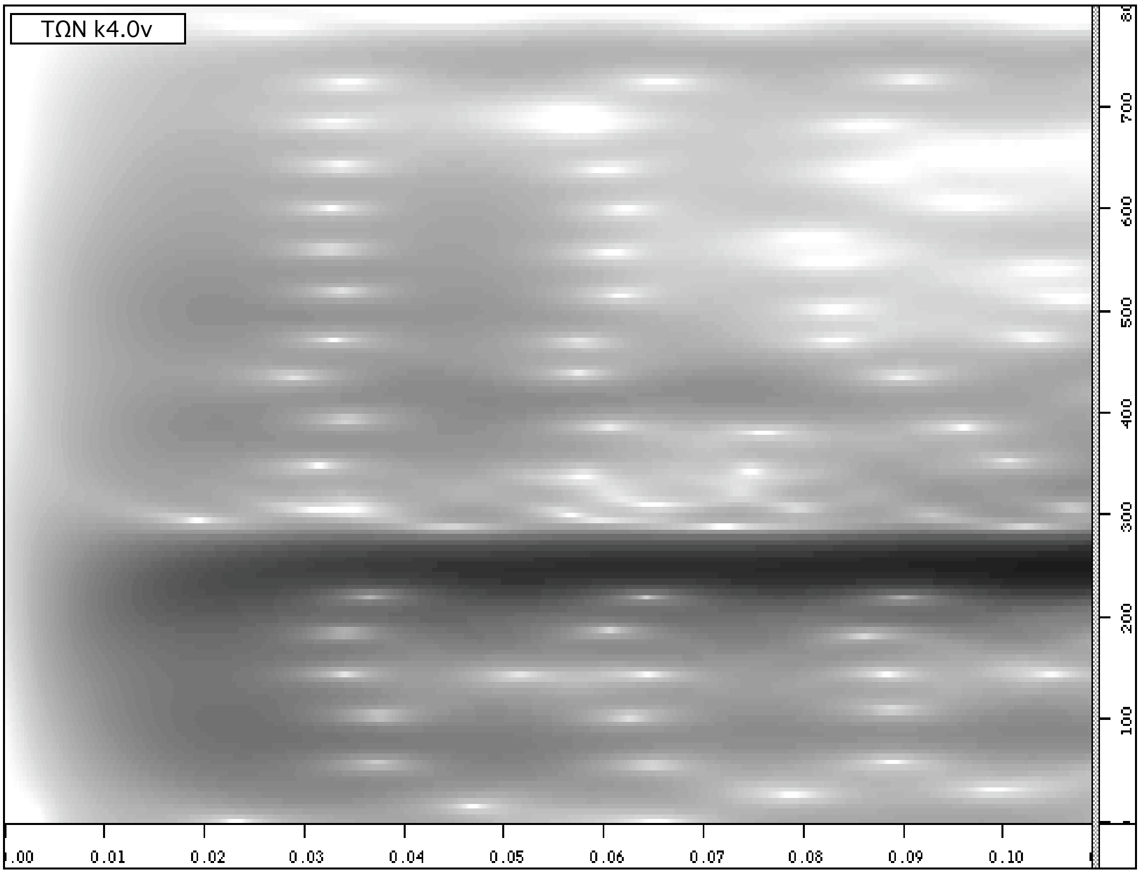
Sonogram 1



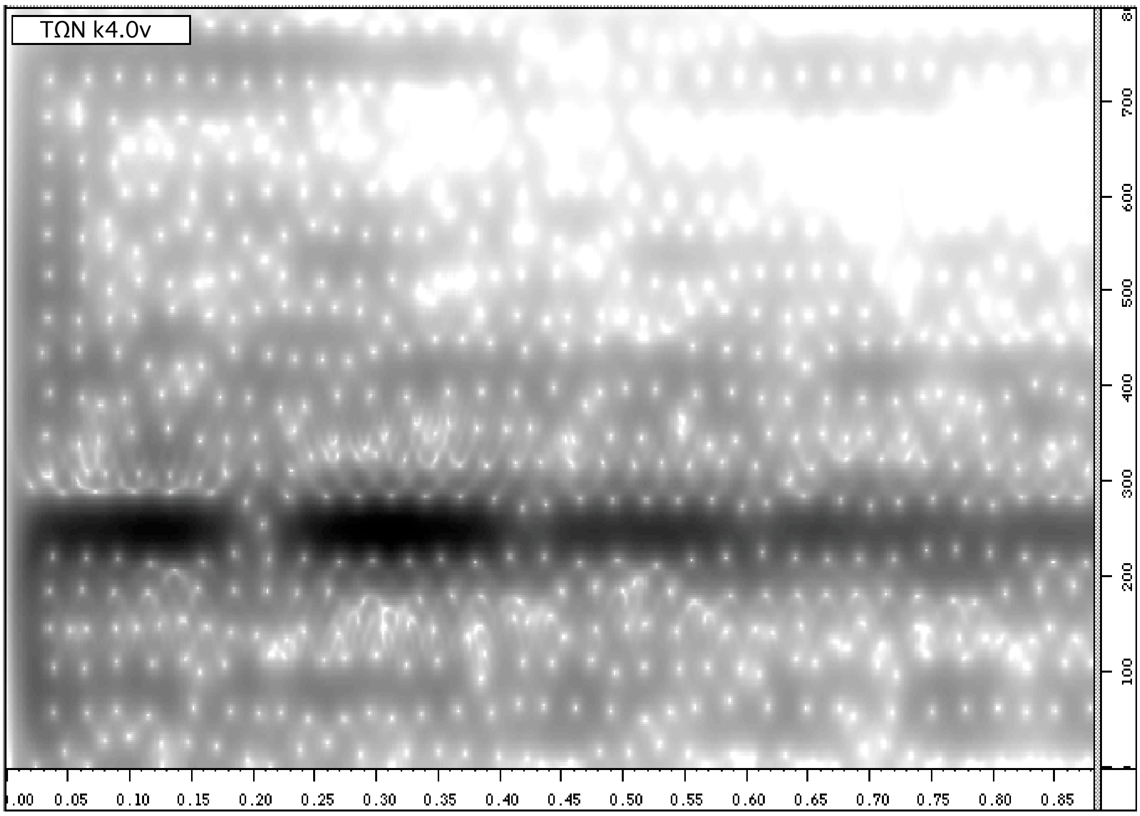
Sonogram 2



Sonogram 3



Sonogram 4



Sonogram 5

Appendix 2 - Glossary

attractor

An attractor defines the state a dynamic system wants to occupy. For example the fixed attractor of water flowing into a sink is the drain. In the original scientific meaning “(...) the attractor state is defined by the minimum of a potential (...).” (Prigogine & Stengers, 1985: 140) There are different types of attractors, which determine the behaviour of systems: fixed attractors (the system reaches a stationary point), cyclical attractors (the system oscillates but is stable) and strange attractors (all other systems) (see Gleick, 1988: 374). A system can have more than one attractor and the transition between them can be initiated by catalysis or perturbence which push the system towards a bifurcation point.

bifurcation

Alvin Toffler describes Ilya Prigogine’s definition of bifurcation points: “In Prigoginian terms all systems contain subsystems, which are continually ‘fluctuating.’ At times, a single fluctuation or a combination of them may become so powerful, as a result of positive feedback, that it shatters the preexisting organization. At this revolutionary moment - the authors call it a ‘singular moment’ or a ‘bifurcation point’ - it is inherently impossible to determine in advance which direction change will take (...)” (Prigogine & Stengers, 1985: xv)

catalyst

“(...) catalytic activity [is] the ability to force a dynamical system from one attractor to another.” (De Landa, 1997: 291) The form of an attractor is given by the system but the strength of attraction is a function of catalysis.

comb filter

If two identical signals are delayed by a small amount of time a set of harmonically related frequencies will be filtered out (see below). This happens because the phase difference between the two signals is exactly 180° for these frequencies, which leads to cancellation.

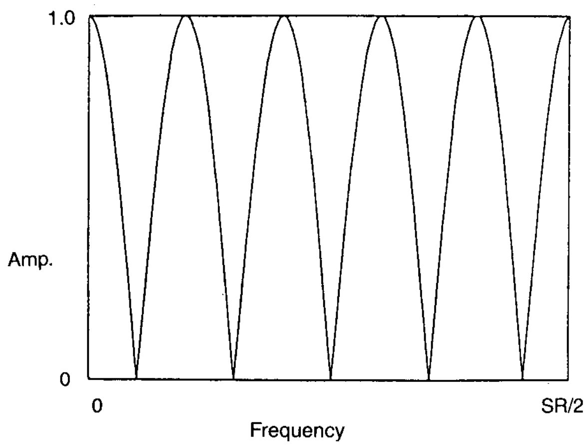


Diagram 6: Comb filter frequency response (taken from Roads, 1996: 414)

electroacoustic feedback

I have borrowed this terminology from David Lee Myers' article in the Resonance magazine (see Myers, 2002: 12,13). Electroacoustic feedback means audible feedback that, during the process of feeding back, passes the electronic as well as the acoustic medium (air).

electronic feedback

This term is also taken from David Lee Myers' article in the Resonance magazine (see Myers, 2002: 12,13). Electronic feedback happens purely in the electronic domain. "It can operate - feed back - eternally, but make no sound; vibrate no air; reach no ears." (Myers, 2002: 12)

feed forward

Feed forward or future feedback describes a concept where future happenings are influenced through feedback loops with the present. According to Charles Muses these processes are expressed as wishes, aims, anticipation, desire, predictions, hopes and expectations. (see Muses, 1985: 59 -72) Feed forward requires the (at least local) suspension of the linear characteristics of time.

negative feedback

"The classic example of negative feedback is the thermostat. A thermostat consists of at least two elements: a sensor, which detects changes in ambient temperature, and, an effector, a device capable of changing the ambient temperature. The two elements are coupled in such a way that whenever the sensor detects a change beyond a certain threshold it causes the effector to modify the surrounding temperature in the opposite direction. The cause-and-effect relation, however, is not linear (from sensor to effector) since the moment the effector causes a change in the surrounding temperature it

thereby affects the subsequent behavior of the sensor. In short, the causal relation does not form a straight arrow but folds back on itself, forming a closed loop. The overall result of this circular causality is that ambient temperature is maintained at a given level." (De Landa, 1997: 67)
In music technology all of the processes summarised under 'dynamics' (such as compression, expansion, gating, etc.) utilise negative feedback control.

phase

Periodic waves can be described by amplitude and frequency (wave length). To understand their interaction in feedback processes the relationship between different waves have to be known. These can be expressed as phase differences. Not only do waves have to be related in frequency but they also need to be in phase (have the same starting point of their cycles, not unlike lasers) to produce feedback. The control of the phase is therefore an important tool to control feedback.

positive feedback

"The turbulent dynamics behind an explosion are the clearest example of a system governed by positive feedback. In this case the causal loop is established between the explosive substance and its temperature. The velocity of an explosion is often determined by the intensity of its temperature (the hotter the faster), but because the explosion itself generates heat, the process is self-accelerating. Unlike the thermostat, where the arrangement helps to keep temperature under control, here positive feedback forces temperature to go out of control." (De Landa, 1997: 67)

resonance

In general resonance means that a relatively small oscillatory force can have a strong effect when the system the force acts on is sympathetic to the frequency of the force. In musical terms resonance occurs when small sounds become amplified through the characteristics of the instrument. Resonance is the predecessor to positive feedback where the system becomes self-oscillatory.

room mode

The resonant frequencies of a room at which electroacoustic feedback is most likely to occur are called room modes. In simple cases the room mode frequencies are those of standing waves between parallel walls (with the wave length of the frequency being a multiple of the room length), in more complex cases all aspects of the room have to be considered and predictions of room modes become very difficult.

Appendix 3 - Comments on the CD tracks

CD 1

All tracks on CD 1 are solo improvisations played on my feedback set-up (see 2.1.3.) with no additional external inputs (except tracks 3+6, see below). They were recorded in real time with end point edits on tracks 2, 3 and 8.

Track 1 - TΩN k5.1 (10:23)

This piece is a study of very low frequencies and modulation in two parts. In the first part very low frequencies are produced and their likeliness to produce clicks is exploited together with pulsing subsonic modulation. A high frequency radio feedback loop is introduced which is subjected to modulation by the changes in the low frequency loop. The second part begins after about 5 minutes and allows slots of broad frequency reverb feedback to emerge, the whole structure slowly becomes less static. After another 2.5 minutes outbursts of radio feedback introduce very high frequencies including ultrasonics plus their eerie alias frequencies mirrored off the Nyquist frequency of the digital equipment, which end in a feedback overload that is finally cut back to a sine wave-like stable end tone.
Because of the use of extreme frequencies this piece should be listened to on very high quality sound systems or headphones.

Track 2 - TΩN k5.2 (4:22)

A quite rhythmical start here gives way to the phenomenon of radio feedback crackling, which I like very much. The irregularity of its onset is caused by several unpredictable modulation signals, which give it an almost organic dirty feel. After it dies away there are only pure tones left.

Track 3 - TΩN k5.3 (1:43)

The sounds on this track are almost exclusively produced by a hearing aid that was placed in a closed empty plastic tub. One side of the headphones of the hearing aid was cut off and turned into a jack output to the mixer while the other side was placed on the lid of the tub to create a feedback loop with the highly sensitive microphone inside the tub. The sounds were created by moving the headphone part around on the lid, which acts like a drum skin, applying different pressure to it. Some difference tones that emerge result from me singing onto the lid at slightly lower or higher frequencies to find the system's bifurcation points where it changes to new feedback frequencies. The piece is dedicated to Otomo Yoshihide.

Track 4 - TΩN k5.4 (6:05)

This almost ambient track is based on a loop I sampled earlier in the session that remained in the volatile memory of the Lexicon JamMan. For me it has a meditative quality that is not disturbed by the introduction of more noisy layers during the piece.

Track 5 - TΩN k5.5 (2:46)

The mute button on my mixer is the main feedback control in this track/study, which highlights the sonic evolution a feedback system goes through to reach a stable attractor. Again there are very low frequencies that might not be reproducible by every playback system.

Track 6 - TΩN k5.6 (7:55)

Starting with low volume radio feedback modulations, on this occasion I encounter the interference of a radio station near the frequency of my FM transmitter. This is unusual as it is tuned to roughly 107.7 MHz, a frequency that is normally not occupied by a station. Thrown by the sudden appearance of the voices I launch into a counter action of drowning out these external interferences with a mass of distortion, building up a noise storm that is channelled through the radio feedback loop. Given that my FM transmitter reaches a radius of about 50 meters I would love to know if anyone in the neighbourhood was trying to listen to that particular radio station around 107.7 MHz at that time. It must have been seriously corrupted by my playing.

Track 7 - TΩN k5.7 (4:22)

Another more meditative drone-like track that has an interesting high frequency part towards the end with a strong stereo content. In the end again voices from an adjacent radio station cut in.

Track 8 - TΩN k5.8 (3:47)

Contrary to most of the other tracks this piece is controlled almost entirely by push buttons that switch certain functions (e.g. EQ) on or off. This recording documents the first time I discovered these functions in regards to feedback sounds shortly after I bought the ETEK mixer. The on-off functions of the mixer have added a new palette of immediate changes to my repertoire.

Track 9 - TΩN k5.9 (8:15)

This track is a study of very high and ultrasonic frequencies. A large part of the frequency spectrum produced is outside the human hearing range and also outside the sampling capacity of the processing and recording equipment. The ultrasonic sounds produce audible alias frequencies that are present throughout the piece. I kept all other feedback activities in the higher frequency region to keep the listener's ears focussed on the upper threshold of the human hearing range. The amount of energy conveyed by these extreme frequencies can be directly experienced therefore I suggest a slightly lower playback volume.

Track 10 - TΩN k5.10 (10:54)

In this longer piece a landscape sound carpet develops that is sprinkled with clicks and pops. These are the recurring elements like irregular lamp posts along a road.

Tracks 1 - 6 on CD 1 are recorded by John Wall. Tracks 7 - 10 are recorded by Knut Aufermann. Mastered in 2002 by Knut Aufermann.

CD 2

Track 1 - Improvisation with Lol Coxhill (16:52)

Playing a duo with Lol Coxhill (soprano saxophone) is always a pleasure. His immense experience and musical wisdom makes it so easy to feel comfortable in the situation where I am apparently dependent on his playing for my electronic treatments. But I think it is obvious that this hierarchy is lost after a few seconds and replaced by a complex network of interplay and feedback (see also 2.3. Performance). This live performance took place earlier this year at the Bonnington Centre in London. Due to limitations in the amplification and recording technology, the quality and mix of this track is not as good as I would hope for.
Recorded in 2002 by Tim Fletcher, mastered by Knut Aufermann.

Track 2 - Rough Rain (3:51, excerpt)

For this collaboration with painter Marcus Heesch, two recordings of the live performance, one made from a stereo microphone in the room and one directly from my mixer, were mixed together to give a glimpse of the atmosphere where painting becomes a sonic activity. I decided to incorporate the earth hum produced by the contact microphones that were mounted on the canvas, and the electronic sounds are a mixture of electronic and electroacoustic feedback and live sampling and processing of the contact microphone signals. The visual result of the session is depicted below (see also 2.3. Performance).

Marcus Heesch, *Rough Rain*, 75 cm x 140 cm, jute, casein eggtempera-ground, eggtempera, piezo speakers.
Recorded in 2001 by Marcus Heesch and Knut Aufermann, mixed and mastered by Marcus Heesch, edited by Knut Aufermann.

Track 3 - Process experiment 1: Satie (4:14)

Recorded in 2001 by Knut Aufermann.

Track 4 - Process experiment 2: Nirvana (3:07)

Recorded in 2001 by Knut Aufermann.

Bibliography

Annett, J. (1969) *Feedback and Human Behaviour* (Harmondsworth, Pengiun)

Aufermann, K. (2002) *Feedback is everywhere*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Barger, *R. Sounds from Chaos in Chua's Circuit*, http://evlweb.eecs.uic.edu/EVL /VROOM/HTML/PROJECTS/57Bargar.html (10/4/02)

Binnig, G. (1992) Aus dem Nichts - Über die Kreativität von Natur und Mensch (München, Piper)

Cary, T. (1992) *Dictionary of Musical Technology* (New York, Greenwood Press)

Chambers Dictionary of Science and Technology (1974) Revised Edition, Eds. T. C. Collocott & A. B. Dobson (Edinburgh, W & R Chambers)

Charles, D. (1989) *Zeitspielräume - Performance Musik Ästhetik* (Berlin, Merve)

Currington, M. (1995) http://www.digital-daydreams.com/tech/audio/ samplefx.asp (20/3/02)

De Landa, M. (1997) *A Thousand Years of Nonlinear History* (New York, Swerve)

Durrant, P. (2002) *Other Kinds of Feedback*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Ernst, D. (1977) *The Evolution of Electronic Music* (London, Collier Macmillan)

Fiske, J. (1990) *Introduction to Communication Studies*, 2nd edition (London, Routledge)

Gleick, J. (1988) *Chaos - die Ordnung des Universums* (München, Knaur)

Ivanovas, G. (2002) *Was ist Wissenschaftskunst* (private correspondence)

Lucier, A. (1995) *Reflections - Interviews, Scores, Writings* (Köln, MusikTexte)

Maturana, H. & F. Varela (1987) *Der Baum der Erkenntnis - Die biologischen Wurzeln des menschlichen Erkennens* (Goldmann)

Mayer-Kress, G., I. Choi & R. Bargar (1994) *Sound Synthesis and Music Composition using Chua's Oscillator*, http://www.ccsr.uiuc.edu/People/ gmk/Papers/NOLTA93/nolta111/nolta111.html (10/4/02)

Mc Graw-Hill Encyclopedia of Science & Technology (1997) 8th Edition (New York, McGraw-Hill)

Muses, C. (1985) *Destiny and Control in Human Systems* (Boston, Kluwer)

Myers, D. L. (2002) *A Personal Journey Through the Ourobouros*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Nakamura, T. (2002) *A Few of my Waking Times*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Pentos Fray Bentos (2002) *Feedback at the Limits of Precise Control*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Pohlmann, K. C. (2000) *Principles of Digital Audio*, 4th edition (New York, McGraw-Hill)

Prigogine, I. & I. Stengers (1985) *Order out of Chaos - Man's new dialogue with nature* (London, Fontana)

Prigogine, I. (1980) *From Being to Becoming: Time and Complexity in the Physical Sciences* (W. H. Freeman)

Prime, M. (2002) *Explorations in Bioelectronics*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Roads, C. (1996) *The computer music tutorial* (Cambridge, MIT Press)

Rogalsky, M. (2002) *David Tudor's Untitled: Feeding Forward*, Resonance Vol.9 No.2 (London, London Musicians' Collective)

Stockhausen, K. (1968) *Nr. 12, Kontakte, Elektronische Musik, Realisationspartitur* (London, Universal edition)

Strange, A. (1972) *Electronic Music - Systems, Techniques, and Controls* (Wm. C. Brown Company)

Varela, F. (1985) *Der kreative Zirkel*, in: Die erfundene Wirklichkeit, editor P. Watzlawick (München, Piper), English version at http://members.ozemail .com.au/˜jcull/articles/artcircularity.htm (26/9/01)

Discography

Karlheinz Stockhausen, *Kontakte* (CD 3 Etude (musique concrete), Stockhausen Verlag: Gesang der Jünglinge, Studie I/II, Kontakte (elektronische Musik))

Alvin Lucier, *I am sitting in a room* (Lovely Music, CD 1013)

Resonance 9.2, *Feedback* (London Musicians' Collective, Magazine CD)