WHY DO FLUTTER ECHOES "ALWAYS" END UP AROUND 1-2 kHz?

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1 INTRODUCTION

Flutter echoes are usually thought of as a defect one wants to avoid, by simple treatments like absorbents or angling/tilting of surfaces. Since the treatments are so simple to understand, flutter has not been investigated much. The physics of flutter echoes is, however, not simple, and flutter sounds quite interesting. The tonal effect of repetitive short sound events is well known from acoustic literature and electroacoustic music; in the Karplus-Strong algorithm and in Stockhausen´s Kontakte [1] which incorporates a transform from tone to pulse/rhythm when the frequency gradually decreases to below some 20 Hz. In daily life, rhythmic reflections are common when an impulsive sound is "trapped" between two parallel, reflecting surfaces in a room with otherwise absorbing surfaces; flutter echoes. The signal must be shorter than, or comparable to the time for the sound to travel the path between the reflecting surfaces, for instance handclaps. Repetitive reflections with Δt [s] between each reflections give a perceived tone with a frequency of $fo=1/\Delta t$ [Hz] and multiples of this; $2fo$, $3fo$ etc. Often this "Repetition Tonality" is used to explain the "tonal" character of a flutter echo in rooms with two parallel, reflecting surfaces and the other surfaces almost totally absorbing. However, $fo=1/\Delta t$ is in the low frequency range (for a distance of 3.43 m between the surfaces, this frequency is 100 Hz, assuming a velocity of sound of 343 m/s), but the characteristic "almost tonal" character of a flutter echo is of mid/high frequency, typically around 1-2 kHz. The aim of this paper is to show different ways of explaining this characteristic timbre of a flutter echo.

This paper shows measurements flutter in actual rooms and anechoic chamber compared with simulations in room acoustics modelling software (Odeon), empirical evaluations, Fresnel-Kirchhoff approximations of diffraction and simulations in MatLab (Edge Diffraction Toolbox). Each of these methods does not fully describe the physics of flutter, but together they give interesting views on what is happening.

The paper will show that the resulting characteristic mid/high frequency timbre of a flutter in ordinary rooms is not a "tone", but a gradual band pass filtering of the broad banded impulsive signal, like a gradual subtractive synthesis. This filtering is a combination of two filtering effects: Low frequency dampening due to the increasing source distance and diffraction, which gives that the sound field is transferred from spherical to plane waves, and High frequency dampening due to air absorption. The sound pressure level of a plane wave is reduced only by air absorption and the absorption at the surfaces, while a spherical wave is reduced by 6 dB per doubling of distance. Together these two main filtering effects give the characteristic mid/high frequency "almost tonal" character of flutter, which we will call the "Flutter Band Tonality" (or just "Flutter Tonality"), as a distinction from the "Repetition Tonality" mentioned above.

Depending on the amount of bass in the signal, its duration and especially the position of the sender/receiver with respect to the resonance peaks and nodes of the standing wave pattern of the room resonances between the surfaces (called $f_{res,o}$ etc), the "Repetition Tonality" (fo. $2fo$….) will appear, but for most positions between the reflecting surfaces, the Flutter Band Tonality "tail" in mid/high frequencies will last longer. In App. E we will see that there is also a third tonality that we might call the "Fresnel Zone Tonality". App. F shows that the timbre of flutter can be used as an audio effect.

2 MEASUREMENTS OF FLUTTER ECHOES

2.1 Flutter Tonality/"Tail"

A typical measurement of a flutter echo in a foyer with absorbent ceiling and two reflecting, parallel walls is shown in fig. 1. (Taken from an Impulse Response measurement, see App.A)

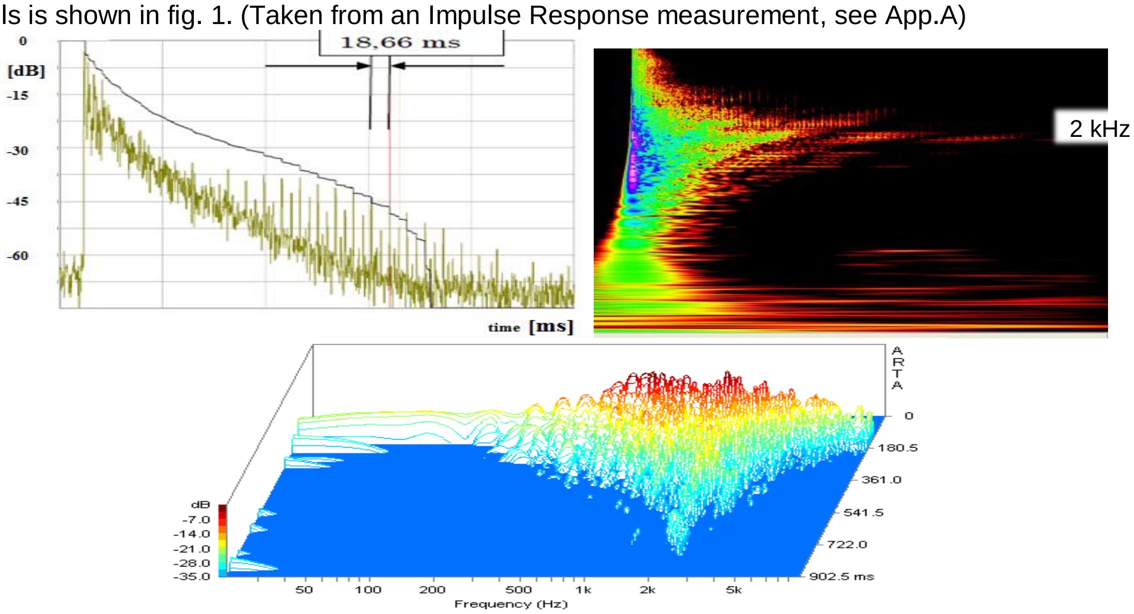

Figure 1: *Decay, Spectrogram (Wavelet) and Waterfall of a typical flutter echo*

We see that the decay ends up in a "tail" around 2 kHz. App.A shows several similar examples of such a mid/high frequency "tail", almost like a gradual subtractive synthesis. In App.A we also find that when the surfaces are somewhat absorbing for high frequencies, this "tail" appears at a somewhat lower frequency. The influence of such a small amount of absorption at the surfaces of and of the actual geometry will be further discussed in Part 4.

2.2 Repetition Tonality/Room Resonances/Standing Waves

Two parallel surfaces with a distance l [m] give an axial resonance at $f_{res,o}=c/2\pi l$ [Hz] and multiples of this; $2f_{res,o}$ etc. This means that the Repetition Pitch (*fo*) is twice the axial Resonance Frequency, (as even partials: 2,4,6 etc. of the lowest room resonance). The sound pressure distribution of the corresponding standing waves is shown in the lower part of fig. 2. The upper part of fig. 2 shows the decay at *fo* for the measurements with two parallel surfaces in an anechoic chamber, with constant sender position and varying receiver position (1, 2 and 3). (For details regarding the measurement, see [2]). We see that the level and decay highly depends on receiver position; slowest decay for positions close to pressure maximum, closest to the wall. Flutter is most commonly perceived when clapping at positions not very close to walls. Also, the result is reciprocal for sender/receiver, and in practice, both sender and receiver must be positioned at points of maximum sound pressure levels of $2f_{res,o}$ etc. in order for the resonances between the surfaces to be of importance. Unfortunately we could not measure exactly in the center, but generally: Even though $2f_{res,o}$ etc. represents "standing waves", we shall see in Part 7 that the Repetition Tonality Band "stands" even longer. For signals with little energy in the bass (handclaps), the impact of room resonances/standing waves is even smaller.

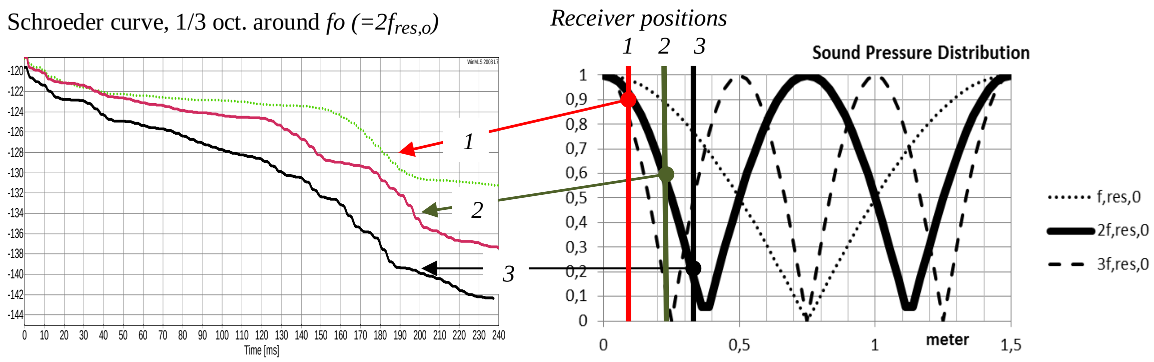

Figure2: *Schroeder curves showing the decay at different receiver positions between the surfaces*
Distance between surfaces:1.5m, fo=114 Hz

For bigger rooms, *fo* (=2$f_{res,o}$) will be much lower than the frequency of most common signals. Repetition Tonality might appear for *2fo*, *3fo* etc., but their corresponding room resonances are generally weaker than for *fo*. The 1/12 octave frequency resolution of the “tail” in the waterfall curves in fig. 1 and App.A give much closer details of the decay than the standardised 1/3 octave resolution for reverberation time measurements (T30). Therefore, the “tail” is not as clearly shown in reverberation time measurements. Some interesting facts can, however, be investigated through reverberation time of flutter echoes.

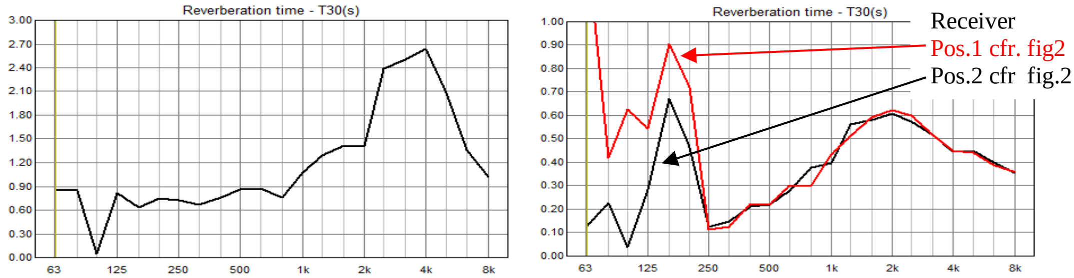

Figure 3: Reverberation Times of flutter.
Left: Foyer (as in fig.1) Right: Anechoic chamber, for two receiver positions

In fig. 3 we see the characteristic peak at mid/high frequencies, but the sharp details for this “tail” is not clearly shown in T30, even for 1/3 octave analysis. (In fig.3, left, it is interesting to notice that the reverberation time for the 1/3 oct. around *fo* changes with receiver position, which confirms the findings in fig. 2). The set up in the anechoic chamber (see App.A) allowed for additional measurements of reverberation times (T30) for different angles between the two surfaces. In fig. 4 we see that, for constant sender/receiver positions, just a small angling of the surface give reduction in the flutter, and that the lower frequencies (*fo*, *2fo*) are not influenced by such small angles, because the changes in geometry due to the angling are much smaller than the actual wavelength.

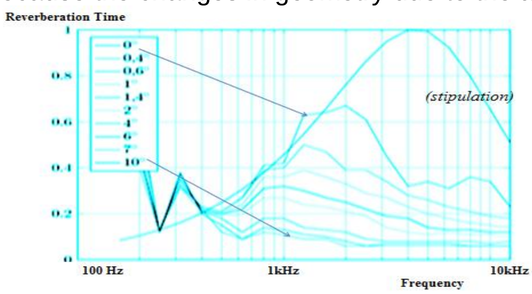

Figure 4: *Rev. time in anechoic chamber.*
Reduction of flutter for increasing
angle between the surface.[2]

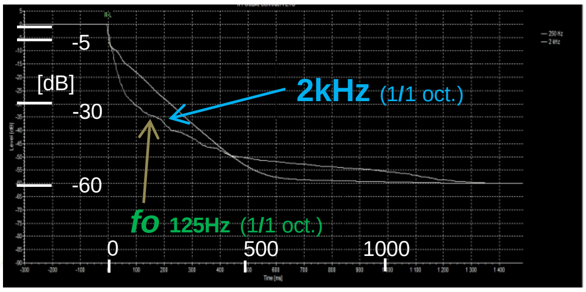

Figure 5: *Decay of sound between two surfaces.*

Fig. 5 shows that for the measurement in the anechoic room, the mid/high frequencies (2kHz) have a linear decay (which indicates a plane wave), but for the octave around *fo* we see the decay of a spherical wave. We need to look further into aspects of spherical and plane waves.

3 ROOM ACOUSTIC MODEL OF FLUTTER

Spherical to plane waves

A very simple Odeon [3] room acoustics model with two parallel, reflecting surfaces was prepared (with all other surfaces totally absorbing). Figure 6 shows the radiation from a point source (spherical wave). The dimensions are as for the measurement in section 2.2. The receiver position is almost the same as the sender (as for a person clapping) and these are both positioned closer to the bottom of the surfaces, giving the possibility to inspect the situation both for a small surface (in the upper part of each figure) and a bigger surface (in the lower part of each figure).

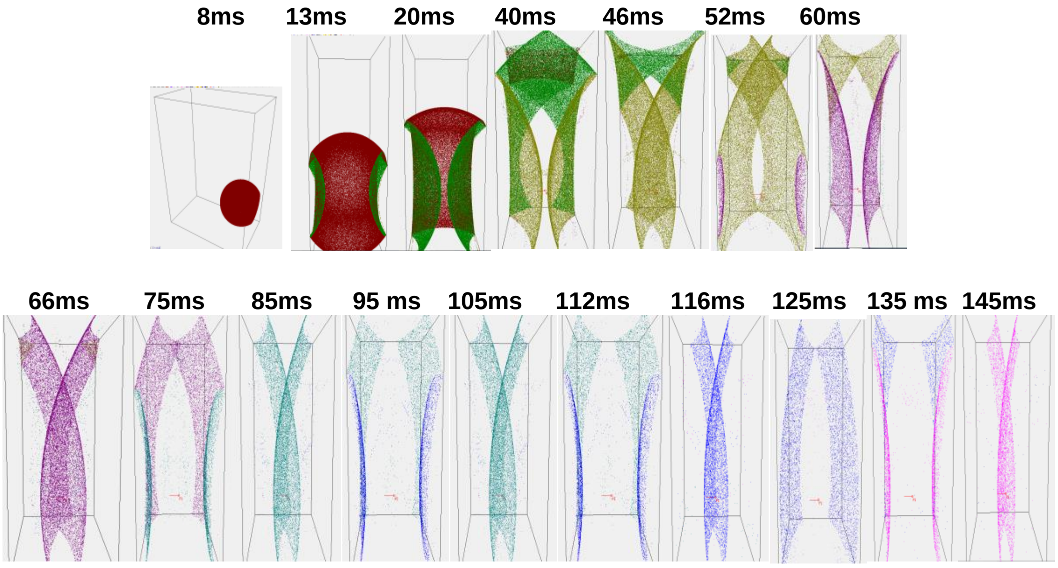

Figure 6: *Snapshots of flutter between two surfaces(Odeon simulation)*

We see that the propagation changes from a spherical to almost a plane wave after just a few reflections. It is interesting to notice that from 9^{th} reflections and upwards to maximum for the Odeon program, we lose almost no "particles" (as they are called in Odeon) in this simulation. I general, the sound pressure level of a spherical wave is reduced by 6 dB pr. doubling of distance, while a plane wave is affected only by air absorption (and possibly of absorption at the surfaces). The reason for the transformation from spherical to plane waves is that the distance from the mirror source to the corresponding reflecting surfaces grow very fast. If we call the distance from source to surface a_1, and surface to receiver a_2 it is visualised in App. B that a_2 will remain constant, but a_1 will grow very quickly as the mirror source moves further and further away from the reflecting surface for each "flutter-reflection". For the n^{th} reflection $a_{1,n}= (2n-1)a_{1,0}$. The transition from spherical to plane is frequency dependent, as shown in fig.5. More studies on the transformation from spherical to plane waves are shown in App. B.

4 INFLUENCE ON DIMENSIONS AND ABSORPTION. KUHL´S EQUATION

Flutter was investigated by Maa [4], Krait et al. [5] and Kohl [6]. Both [5] and [6] states that for a plane wave between two surfaces S [m^2] with distance l [m], the wave is dampened only by the absorption coefficients α at each surface and the air absorption, m. (frequency dependent). App. C gives the background for Kuhl´s equations. The frequency content of flutter can be looked upon as the "sum" of three reverberation "asymptotes" for the reverberation time versus frequency, f: (c is the velocity of sound).

1. Low Frequency damping due to finite surface areas:

$$T_1 = \frac{0.041\ x\ 2fS}{c} \tag{1}$$

2. Damping due to absorption on the surfaces:

$$T_2 = \frac{0.041 \times l}{\alpha} \tag{2}$$

3. Damping in the air (dissipation):

$$T_3 = \frac{0.041}{m} \tag{3}$$

The total reverberation time, T_{FL}, can be re-written as:

$$\frac{1}{T_{FL}} = \frac{1}{T_1} + \frac{1}{T_2} + \frac{1}{T_3} \tag{4}$$

Fig. 11 shows how these three "asymptotes" work together to get the total maximum reverberation for a mid/high frequency band, and how the different parameters influence on the position of the "peak" and, to a certain degree, how narrow this "tail" will be, (the "Q-factor" of the combined filter).

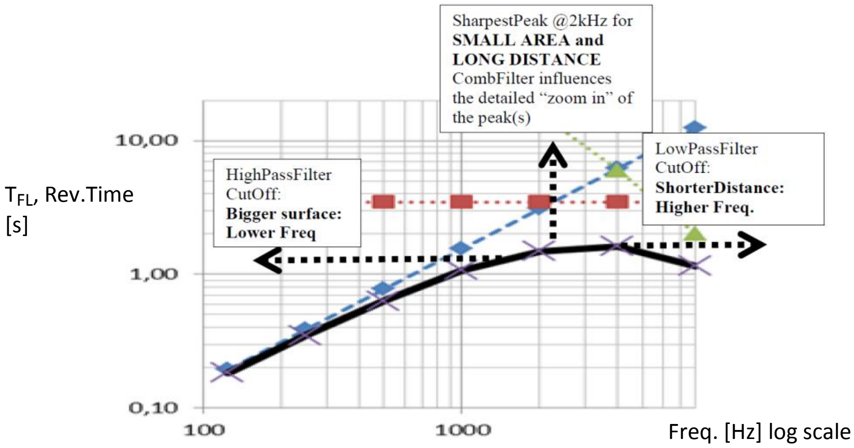

Figure 7: *Illustration of Kuhl´s equation, showing how the different parameters influence the reverberation time of flutter echoes*

For the understanding of flutter, T_1 and T_3 are the most important, and, for simplicity, the absorption coefficient α is set frequency independent and equal for both surfaces. Compared to the measurements in 2.1 and fig. App.A, fig. 7 shows that Kuhl [6] gives a good explanation of what is happening, and we can see how the "tonal" characteristic of the flutter changes with different geometry and minor changes in surface absorption, but the method uses reverberation time only as a parameter, the equation for the effect of non-infinite surfaces is empirical, and the results do not give as sharp "tail"/"Flutter Band Tonality" as measured in actual rooms.

5 CALCULATING DIFFRACTION

5.1 Approximation of Fresnel/Kirchhoff

The behaviour of a physical reflector lies somewhere in between two extremes: Low frequency sound is not affected by a small surface (smaller than the wavelength), and if the reflector is really large, it reflects (almost) all frequencies. Between these extremes, diffraction from the edges influences the frequency response. Before we go into Fresnel Zones more in detail in the next section, we will look at an approximation of edge diffraction for two parallel surfaces. We will start with just one single surface. Fig. 8 shows a typical situation for the diffraction from the edge.

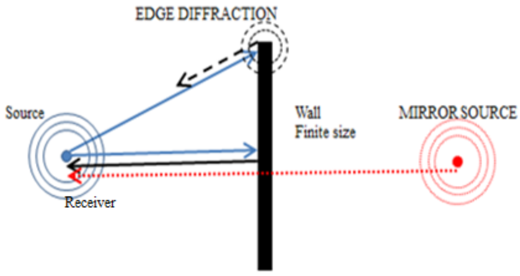

Figure 8: *Mirror source and Diffraction from the edge of a finite surface.*
Receiver is at source position (as for a person listening to his own handclap)

Rindel [7] has developed an approximation of Fresnel/Kirchhoff. (See App. D). The method was developed for a single reflection and for situations where *Source-Surface* distance and *Surface-Receiver* distance are about the same size. For our investigation of flutter, we will disregard these assumptions, and investigate if the method described in App. D gives reasonable results also for repetitive reflections when *Source-Surface distance* quickly grows much longer as the mirror source moves longer and longer away from the reflecting surface(s) (and the wave is transformed from a spherical wave to plane wave). A typical result from such a calculation for the same small dimensions as in section 2.3 (typical dimension 1.5 m) is presented in fig. 9, showing the gradual reduction in the bass as a function of the number of flutter reflections.

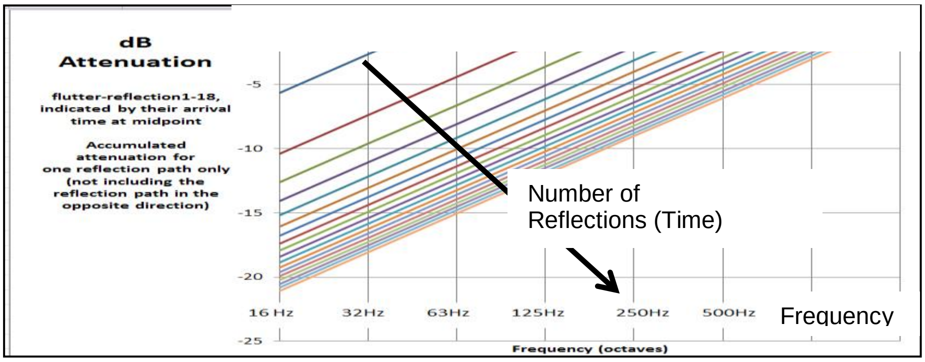

Figure 9: *Attenuation of low frequencies due to repetitive flutter reflections,*
calculated regarding diffraction for gradually increasing sender/surface distance..

This Fresnel/Kirchhoff approximation in fig. 9 shows reasonably good agreement with the measurements for a small surface (in fig.1 and fig. App.A.1). Similar calculations for bigger surfaces however, give that this method does not show as large low frequency damping as measured.

5.2 Fresnel zones

The peaks and dips in the frequency response due to diffraction can be investigated by looking at the Fresnel zones (see App.D), which are shown as circles in fig. 10, left. In rooms with flutter echoes, the surface is often a rectangle, not a circular plate. Then we need to plot the rectangle and the Fresnel Zones for the given source/receiver positions and a given frequency (see fig. 10, left), and see which zone "most of edges" will fall into, in order to find if the edge diffraction will be in-phase or out-of-phase. Fig. 10 (right) shows a typical frequency response due to fiffraction from the edges of a single, non-infinite surface.

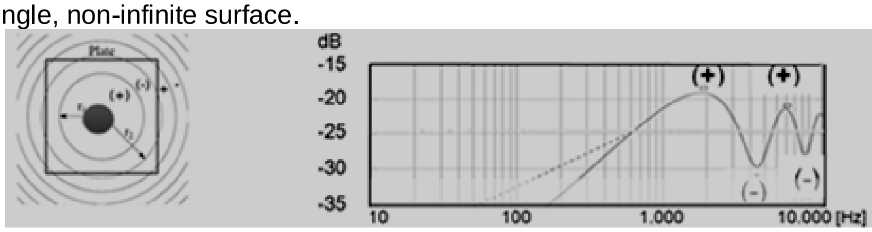

Figure 10: *Fresnel zones and their influence of frequency response [2]*

In App. D it is shown that for repetitive flutter-echoes, the gradually increasing (mirror)source distance gives that the Fresnel radius gradually increases for each flutter repetition, but only up to some 10-12 reflections. Fig. 11 shows that after that, the Fresnel radii are almost constant. This is another way of showing how fast the wave is transformed from spherical to plane. In addition, the Fresnel zones actually give a “FresnelTonality” of minor importance which is described in App.E.

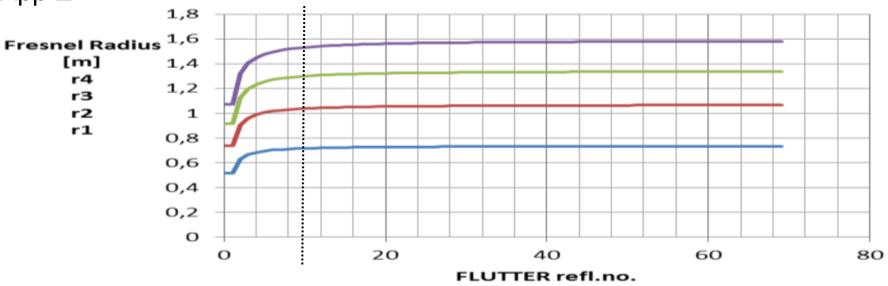

Figure 11: *Fresnel zones radii after repetitive flutter reflections*

6 DIFFRACTION IN MATLAB

Flutter was investigated [2] using EDB (Edge Diffraction toolbox for MatLab) by Peter Svensson [10]. One typical comparison of measured and simulated impulse responses is shown in fig. 12. We see the edge diffraction in the time domain marked with a red, dotted circle.

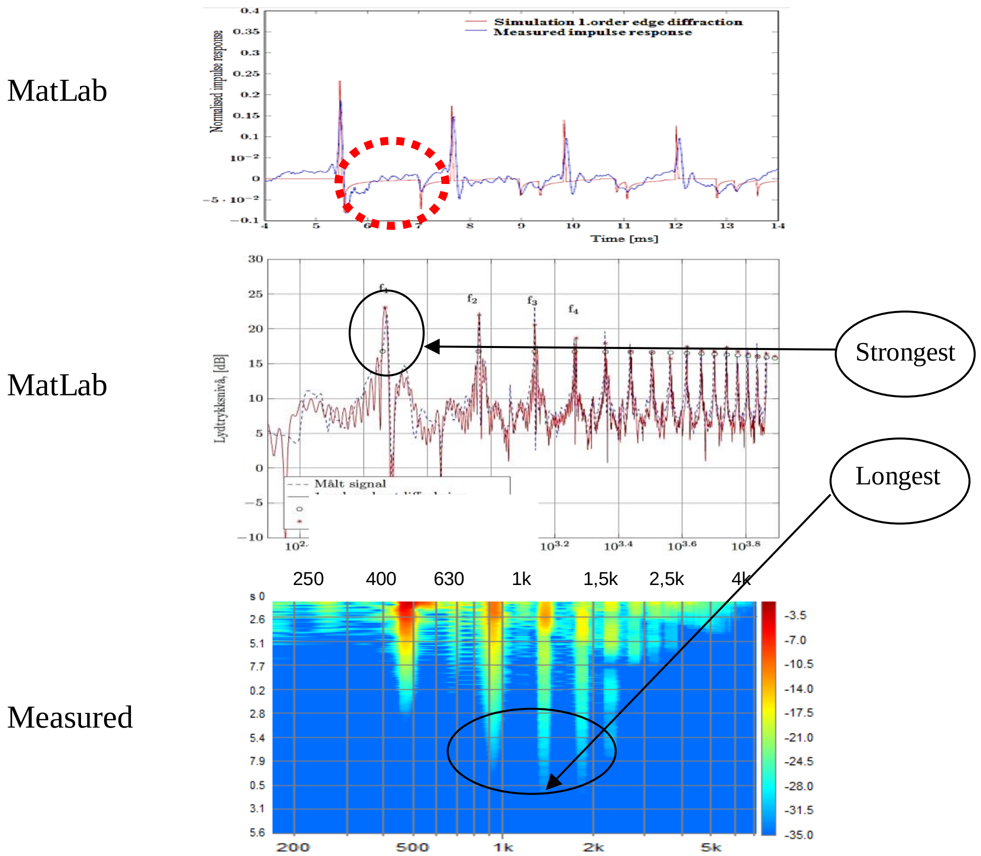

Figure 12: *Comparing measurements and simulations. Imp.Resp., Frequency analysis, Waterfall of measurement*

The middle and lower panes of fig. 12 show comparison of simulated and measured frequency response of flutter. We see that the frequency peaks align pretty well, but, because the maximum number of reflections in the simulation is only 13, the simulation does not include the last of part of the decay of these peaks. Comparing the two lower panes of fig.12, we see that the peaks around

1-2 kHz are not the strongest ones in the simulation, but they last longer in the actual measurement, (lower part of fig.12, which shows the same measurement as the waterfall in fig. 4). As a conclusion: It would have been nice to be able to simulate all aspects of flutter in MatLab, but the method available was not able to simulate longer time stretches than 13 specular reflections.

7 LINKS BETWEEN THE TWO "TONALITIES" OF FLUTTER

The waterfall curves in fig. 13 show the two main "tonalities" a flutter echo. The lowest "hill" (marked 2, red ellipse) indicates the Repetition Tonality ($fo=1/\Delta t$) between the surfaces. For gradually higher frequencies we see the "harmonics" of this resonance ($2fo$, $3fo$ etc.). We see that the mid/high band (marked 1, black ellipses) last longer and one of these "overtones" will of course "win" in the competition of lasting the longest. The fact that a mid/high frequency band last longer than the fundamental of the Repetition Pitch (fo), is therefore not a direct result of the fo-resonance itself, but as we only have the multiples of fo to choose from towards the "tail", there is of course a certain link between the two main "tonalities" of flutter. It is like a subtractive synthesis, a gradual formant shaping like in harmonic (overtone) chant.

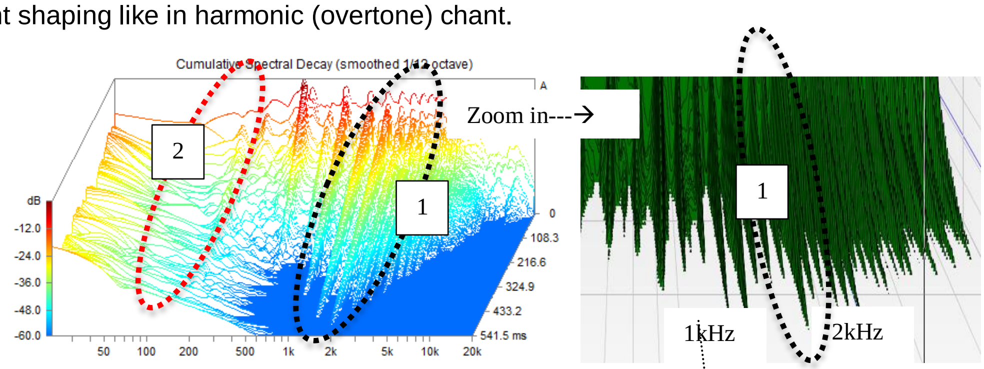

Figure 13: *Waterfall curves of flutter*
"Resonance Tonality"(black), "Flutter Band Tonality"(red). Left: Zoom In

Fig. 14 shows an overview of the two main "tonalities" of flutter. The equally spaced lines (linear frequency axis), are the "overtones" of the "Resonance Tonality" fo. The overall filtering giving the mid/high frequency "tail" is the "Flutter-Band-Tonality" as a result of the High Pass Filter due to non-infinite surfaces and increasing distance between mirror source and surface for each flutter reflection, and the Low Pass filtering due to air absorption. The impact of the Repetitive Tonality (marked 2),combined with the room resonances is highly dependent on positions of sender and receiver, but the flutter filtering towards the "tail"/Flutter Tonality (marked 1) is perceived much easier for all positions.

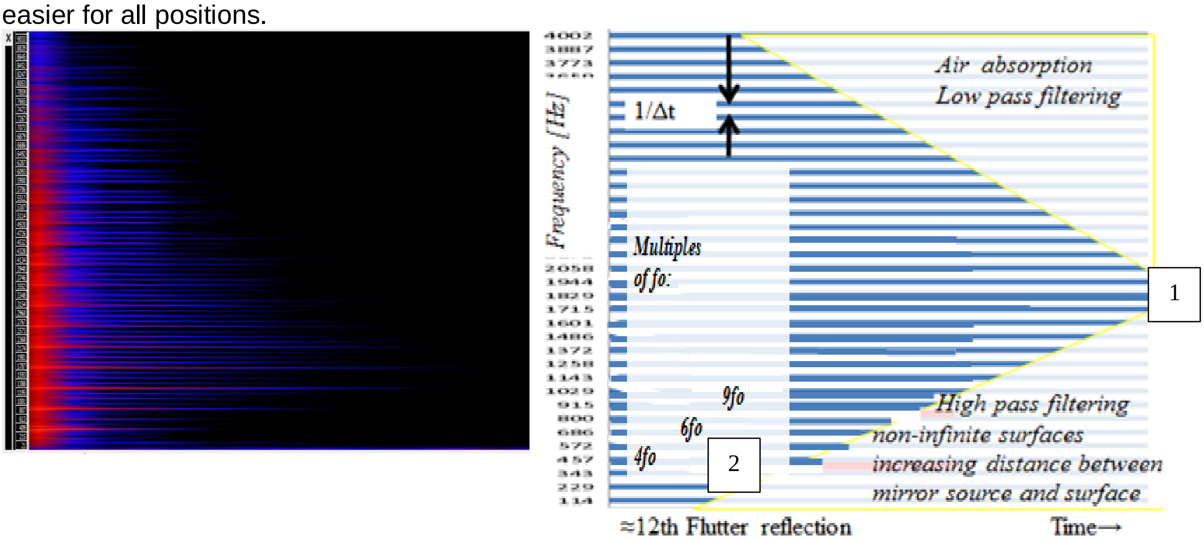

Figure 14: *The two main "tonalities" of flutter.*
Measurement and schematic overview

App. E includes additional remarks on possible comb filter coloration due to flutter, and a “third” tonality that we have called “Fresnel Zone Tonality”. Both these effects are of minor importance compared to the two main “tonalities” of flutter shown in fig.14.

8 CONCLUSIONS

None of the methods discussed can fully describe all the aspects of a flutter echo. However, it is shown that the characteristic mid/high frequency “tail” of a flutter echo is not result of the time between the repetitive reflections (nor the room resonance), but of two filtering effects: The low frequencies are gradually reduced because the surfaces are not infinite, so that the fast growing distance from mirror source to reflecting surface and the diffraction from the edges give a transformation from spherical waves to plane waves. The very high frequencies are reduced due to air absorption. It is shown that flutter has several additional effects, but this gradual filtering towards the “tail” at 1-2 kHz is the most important, giving the characteristic sound of flutter echoes.

9 ACKNOWLEDGEMENTS

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APPENDIX A) MEASURMENTS OF FLUTTER

For clarity, the examples in this paper are for sender and receiver close to each other, placed somewhat half-way between the reflecting surfaces (unless otherwise stated). Separate positions of source and receiver give a double pulse train with time difference corresponding to the travelling time between these, and can be interesting to study, but are not included due to limited space. Fig. App.A.1 shows several flutter echoes measured in several rooms/situations: (Waterfall curves smoothed to 1/12 oct.). Block dotted ellipses indicate "Flutter tail", Red indicate Repetition Tonality.

Anechoic Chamber *Foyer* *Hotel room* *Between two buildings.*

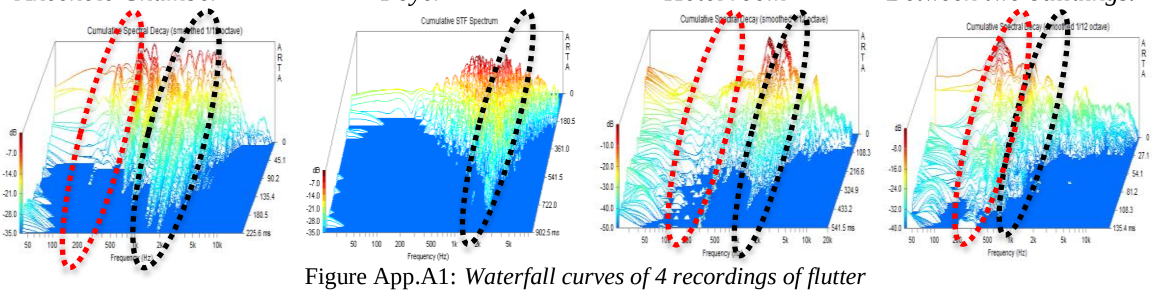

Figure App.A1: *Waterfall curves of 4 recordings of flutter*

The set up for the measurements of Impulse Responses using sine-sweep in anechoic chamber is shown in fig. 3. (See Skjong 2015[2]). Surface area is for practical reasons limited to 1.5 m x 1.5 m. Length between surfaces: 1.5 m. (The yellow Glava is for avoiding reflections from the stands).

Figure App.A.2: *Set up for measurements of flutter in anechoic chamber and hotel room*

The frequency analysis of a hand clap between two buildings outdoors is shown in fig. App.A.1,left. (Surfaces 20 m^2, Distance 7m). Both facades are wooden panel, with app. 1 cm "in/out-structure" and somewhat rough surface. This means additional high frequency absorption, which gives that the "tail"/"Flutter-Tonality" is at a lower frequency than in the first examples. The high background noise is problematic, but the "perceived tonality" is about 500 Hz.

APPENDIX B) MIRROR SOURCES AND ROOM ACOUSTIC MODEL

We will call the distance from source to surface a_1, and from surface to receiver a_2. Fig. App.B.1 shows that a_2 will be constant, but a_1 will quickly and gradually grow as the mirror source moves further and further away from the reflecting surface for each "flutter-reflection". For the n^{th} reflection $a_{1,n}$= (2n-1)$a_{1,0}$. This gives that the spherical wave is transformed into almost a plane wave for mid/high frequencies after just a few flutter-reflections, and the transformation is fastest for small surfaces (see also fig. 6 in the paper)

$a_{1,n}$= (2n-1)$a_{1,0}$

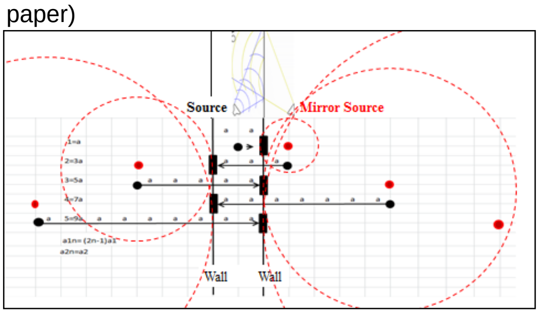

Figure App.B.1: *Distance from mirror source to reflecting surface for increasing number of flutter reflection.*

An Odeon simulation for quadratic surfaces (a room; 1.5 x 1.5 x 1.5m) is shown fig.App.B.2. We see the transformation from spherical to almost plane wave and the diffraction from the edges.

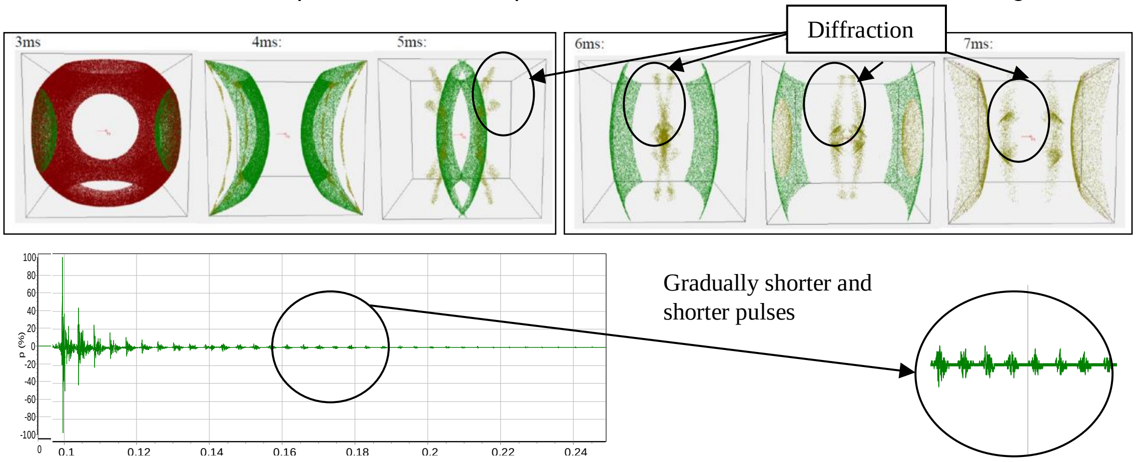

Figure App.B.2: *Snapshots of flutter between two square surfaces and Impulse Response (BRIR-left ear)*

APPENDIX C) KUHL´S EQUATION

Kuhl [6] states that for a plane wave between two surfaces S_1 and S_2 [m^2], the wave is dampened only by the absorption coefficients α_1 and α_2 and the air absorption, m. (frequency dependent). For a plane wave the sound intensity in x-direction (direction of propagation) is:

$$I_x = I_0(1-\alpha_1)^{\frac{x}{2l}} \times (1-\alpha_2)^{\frac{x}{2l}} \times e^{-mx} \qquad \text{(Eq. App.1)}$$

Where I_0 is the initial intensity and l [m] is the distance between the surfaces. After the reverberation time T, the sound intensity is reduced to Ix:

$$\frac{I_x}{I_0} = 10^{-6} = e^{-13.8} \text{ and } x = cT$$

Following, the reverberation time of the flutter echo, T_{FL}, is:

$$T_{FL} = \frac{0.041}{\frac{1}{2l}[-\ln(1-\alpha_1)] + \frac{1}{2l}[-\ln(1-\alpha_2)] + m} \qquad \text{(Eq. App.2)}$$

This equation is for a plane wave with geometrical reflection. In practice, the lower the frequency, and the smaller the areas S_1 and S_2 are, the more the longer waves will not be fully reflected, but partly bended around the edges. Therefore Kuhl introduced an addition in equation Eq.App.2. An empirical approximation is:

$$\frac{\lambda}{2S}, \text{ which can be written as: } \frac{c}{2fS}$$

Equation Eq.App.2 can thus be corrected to:

$$T_{FL} = \frac{0.041}{\frac{c}{2fS} + \frac{1}{2l}[-\ln(1-\alpha_1)] + \frac{1}{2l}[-\ln(1-\alpha_2)] + m} \qquad \text{(Eq. App.3)}$$

Here we have assumed both surfaces are of equal size: S_1=S_2=S.

For reflecting surfaces ($\alpha_{1,2} < 0.2$), we can make the substitution $-\ln(1-\alpha) \approx \alpha$, so the equation can be written as:

$$T_{FL} = \frac{0.04}{\frac{c}{2lS} + \frac{\alpha}{l} + m} \qquad \text{(Eq. App.4)}$$

This can be looked upon as the "sum" of three reverberation "asymptotes" for the reverberation time versus frequency, as given in the paper in Part 4 of the paper.

One might question that air absorption gives such a significant impact, when the air absorption pr. m^3 is not large. However, for a flutter echo, we need to look at the basic background of air absorption, which implies absorption pr. meter sound path, which will be significant after just some flutter reflections.

APPENDIX D) CALCULATING DIFFRACTION

Rindel [7] has developed an approximation of Fresnel/Kirchhoff. The typical dimension of the surface is $2b$. A spherical wave is radiated from source *Q*, with a distance a_1 and an angle θ, as shown in fig. App.D.1. The distance from the surface to the receiver *P*, is a_2. *Q'* is the mirror source.

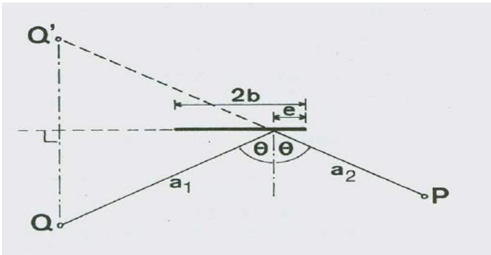

Figure App.D.1: *Diffraction from a finite surface (from [7])*

Rindel [7] states that attenuation due to diffraction is of minor importance above a limiting frequency:

$$f > f_{lim} = \frac{1}{2} \times \frac{\frac{a_1 a_2}{a_1 + a_2}}{(2b cos\theta)^2} \qquad \text{(Eq. App.D.1)}$$

This frequency was taken to be the boarder frequency of the high pass-filter. The dampening due to diffraction of the finite surface relative to an infinite surface is given by equation App.D.2.:

$$\Delta L = 10 log \left(\frac{2b cos\theta}{\sqrt{\lambda \frac{a_1 a_2}{a_1 + a_2}}} \right)^2 \qquad \text{(Eq. App.D.2)}$$

The method was developed for a single reflection, and for situations where a_1 (source-surface) and a_2 (surface to receiver) were about the same size, defining the characteristic distance $a^* = a_1 a_2/(a_1 + a_2)$. For our investigation of flutter, we will disregard this assumption, and investigate if Eq.App.D.2 gives reasonable results also for repetitive reflections when a_1 quickly grows much longer than a_2 as the mirror source gets longer and longer away from the reflecting surface(s); $a_{1,n} = (2n-1)a_{1,0}$, (as the wave is transformed from a spherical wave to plane wave). A typical result from such a calculation for the same small dimensions as for the measurements in the anechoic chamber is shown in fig. 9 in the paper. (For normal incident, $\theta = 0^o$)

Fresnel zones

The behaviour of a physical reflector lies somewhere in between two extremes: In the low end, low frequency sound is not affected by a small surface (smaller than the wavelength). The other extreme is that the reflector is so large that it reflects all frequencies like a mirror. In between these extremes, the response varies depending on the ratio between wavelength and typical dimensions of the surface.

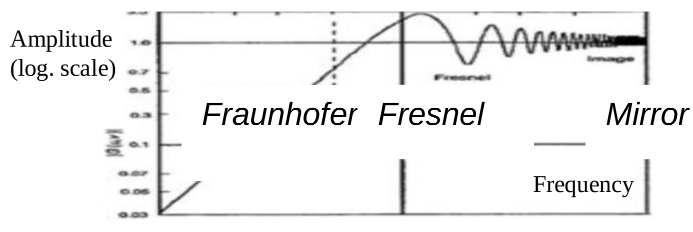

Figure App.D.2: *Overview of the influence of reflection from a circular plate (fig. adapted from [8])*

The received sound at the receiver in fig. 8 (section 5.1) is a combination of the reflection from the surface (the mirror source) and the diffraction from the edges of the surface. Consider a spherical wave of some given frequency sent towards a circular surface. When the surface is small, (see fig. App.D.3a). the sound field will not be affected by an object much smaller than its wavelength. For simplicity (and to simulate a person listening to his own clapping), the receiver (microphone) is positioned at (almost) the same place as the source in these figures. If we gradually increase the radius of the surface (fig. App.D.3b), more and more sound will be reflected, but much less than if the surface was infinite. (Fraunhofer region in fig. App.D.2).

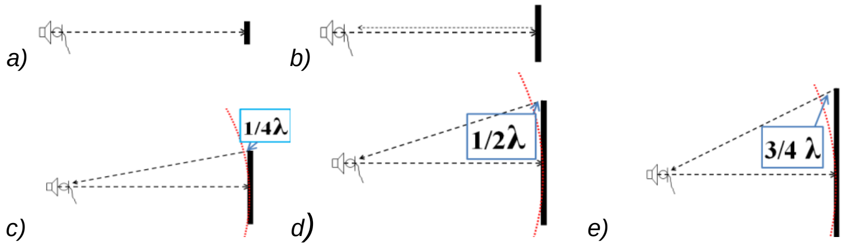

Figure App.D.3 *Visualisation of Fresnel zones by increasing radius of circular reflector. Receiver at source position*

When we increase the radius of the surface, gradually more of the soundfield will be reflected from the surface, (Fresnel Zone1), and gradually more of the sound will be diffracted from the edge of the surface. When the difference in travelling path between the diffracted sound from the edge and the sound reflected from the central region of the surface is half a wavelength ($1/2\lambda$, shown as $2x1/4\lambda$ in fig. App.D.3b), the diffracted sound will be out of phase with the sound directly reflected, and the result will be a reduction at the receiver. We have reached the next Fresnel Zone. (fig. App.D.3c).

If we increase the radius surface further, the difference in travelling path will reach 1/1 wavelength (or $2x1/2\lambda$), so the diffracted sound will be in phase with the direct reflection, and there will be an increase in sound pressure level at the receiver. We have reached the next Fresnel Zone. (fig. App.D.3d). When we increase the radius even further, we will get the higher order Fresnel Zones, with successively in-phase and out-of-phase situations. (fig.App.D.3.e). A more generalised situation is shown in fig. App.D.4, allowing separate positions of source and receiver.

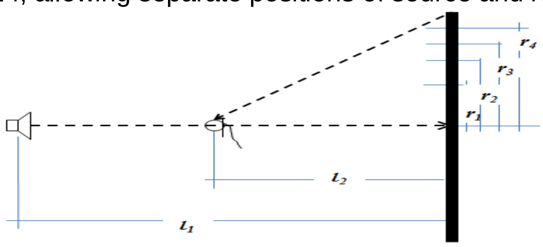

Figure App.D.4: *Visualisation of Fresnel zones. Generalised source-/receiver positions*

For the diffracted sound to be either out-out phase or in-phase, the difference between the diffracted reflection and the mirrored reflection must be a multiple n of half the wavelength, λ, see [9] and [2].

$$\Delta l = \sqrt{l^2{}_1 + r^2{}_n} + \sqrt{l^2{}_2 + r^2{}_n} - l_1 - l_2 = n\frac{\lambda}{2} \qquad \text{(Eq.App.D.3)}$$

which gives:

$$r_n = \sqrt{\frac{\left(\left(n\frac{\lambda}{2}+l_1+l_2\right)^2 + l_2{}^2 - l_1{}^2\right)^2}{4\left(n\frac{\lambda}{2}+l_1+l_2\right)^2} - l_2{}^2} \qquad \text{(Eq. App.D.4)}$$

In the case of flutter echoes, the surface is often a rectangle, not a circular plate. Then we need to plot the rectangle and the Fresnel Zones for the given source/receiver positions and a given frequency, and see which zone "most of edges" will fall into, to see if the edge diffraction will be in-phase or out-of-phase. Fig. 10 in the paper shows an example from [2].

APPENDIX E) COLORATION AND A THIRD FLUTTER TONALITY

Coloration

One or more repetitive reflections will always give some kind of comb filtering; see [12] and [13]. The frequency band of the “Repetition Tonality” for flutter echoes will give a “Box-Klangfarbe” (a Comb-Between-Teeth-Bandwidth in the order of Critical Bandwidth) for most common rooms in dwellings, for as long part of the decay as the Flutter Tonality pass band is broad enough to include sufficient amount of dips and peaks in the comb. For the last part of the flutter echo, the “tail” will include too so few dips and peaks that the subtractive synthesis has reached almost a pure tone, (a comb with very few teeth).

Fresnel Zone Tonality

A third tonality of flutter might be called the “Fresnel Zone Tonality”. This is not as easily perceived as the two main tonalities, and is highly dependent on geometry. The reflections from the edges of the surfaces form an additional rhythmic pattern which gives small extra lines in the specter. The difference in frequency between the lines is a function of the typical dimension of the surface (the closest Fresnel radius). As shown in fig. 11, the Fresnel radii increase for flutter reflections up to some 10-12. This gives that the Fresnel Zone Tonality shows small glissandi downwards for the first flutter reflections, as the radius of the Fresnel zones increases (see fig.App.E.1).

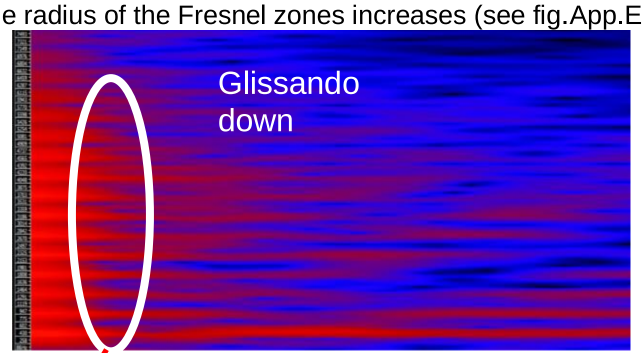

Figure App. E.1: *Zoom in on start (13reflections) of flutter. Glissando due to changes in Fresnel Radii in the first part of the decay*

Fig. App.E.2 shows measurement showing this “Fresnel tonality” of flutter, marked (3) in the upper part of the figure, and in the lower part it is included in the schematic overview from fig. 14:

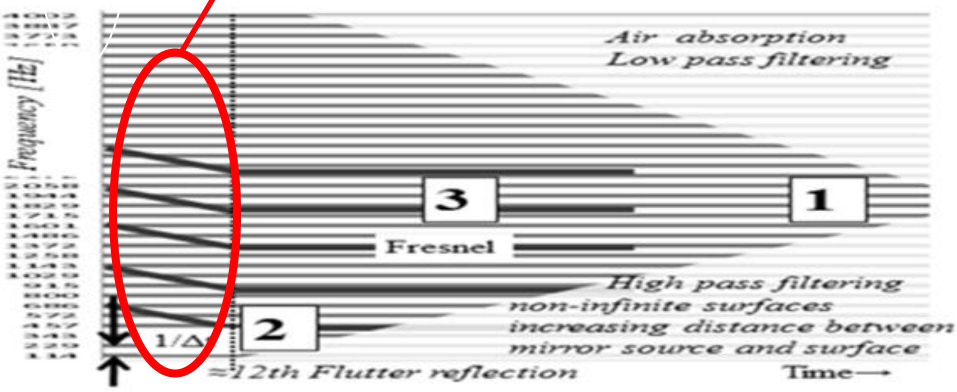

Figure App. E.2: *Fresnel “tonality” included in the overview from fig. 14*

APPENDIX F) FLUTTER AS AN AUDIO EFFECT

The main issue for this project was to understand what is happening when flutter echo appears, but as a test, simplifications of the equations shown in this paper were put into a simple Max/Msp patch. Some “musical” tests of this Flutter-patch with different music/speech as signals can be downloaded from: www.tor.halmrast.no. By changing the “geometry” in the Max/msp simulation, one can gradually change the amount of filtering up to non-realistic situations. The effect is different from ordinary delay/comb filters because the characteristic “tonality” is not (directly) depending on the repetition rate, but will “always” end up in a mid/high frequency range, typically around 1-2 kHz.