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# The Great Highland Bagpipe

**T**HIS article aims to illustrate some of the features of the tuning of the Highland bagpipe scale in terms of the consonance and dissonance of the chanter against the drones. It presents a theoretical plot which estimates how the sensory dissonance varies for every possible tuning of the chanter. This is achieved by charting a steady glissando from low G to high A, using different colours for the different numbers of harmonics present in chanter, tenor drone and bass drone spectra. Such a visual representation may be of practical assistance to players, reed makers and bagpipe makers who are seeking to achieve a better sound. It also offers a new understanding and clearer explanation of why the bagpipe scale is non-standardised.

## Harmonics on the bagpipe and dissonance

THE bagpipe produces sound through the air in the bag acting as a high-pressure reservoir, with the reeds partially opening and closing to allow periodic puffs of air into the drones and chanter. Each pipe produces a pitched musical sound consisting of a harmonic series (pure tone components within the sound that blend together, producing a unique tone colour). The lowest component in a harmonic series is not always the loudest, but is labelled the fundamental frequency and this depends principally on the length of the air column enclosed. When multiple frequencies are sounding simultaneously (as in chanter and drones), the degree of pleasantness or consonance in the sound depends on the extent to which harmonics coincide.

When pure tone harmonics from two different sounds are very close to each other but not matching then beating may be perceived in the sound (as observed during tuning). If the difference is slightly too large for beats to be observed then a very rough, dissonant sound is perceived. Listening tests have concluded that the sensory dissonance has a maximum which typically occurs when the difference in frequency between two pure tone components in the sound is around a semitone (but this

depends on the frequency) as illustrated in Figure 3.8 of Sethares' *Tuning, Timbre, Spectrum, Scale* [1].

## Graphs of sensory dissonance

IN 1995, MacKenzie [2] demonstrated the range of tone colours produced by drones and chanters and considered the implications for intonation. He also reproduced a graph by Kameoka and Kuriyagawa [3] covering the dissonance for harmonic tones in a range of less than an octave. As MacKenzie states, such a plot represents the dissonance of a chanter glissando against another chanter sounding low A, rather than against drones sounding in lower octaves. The graph in this article is more relevant to Highland pipers because it plots sensory dissonance of the chanter against pitches corresponding to the tenor and bass drones.

Using MATLAB programs customised from those of Sethares [1], the proximity of all the harmonics of the drones were checked in relation to all the harmonics of the (variable) chanter pitch. The total amount of sensory dissonance was then tallied up and the results are graphed in Figure 1. It should be noted that no sound synthesis or listening tests on actual bagpipe tones were performed, but rather a standard method was applied to predict relative dissonance levels.

Different coloured lines on the figure show how the sensory dissonance depends on the number of harmonics (or tone colour) of each sound source: bass drone, tenor drones and chanter. The horizontal axis shows chanter fundamental frequencies, as measured relative to a low A that is perfectly in tune with the bass drone two octaves below and tenor drones one octave below. Dips on each line show frequencies that my theoretical modelling predicts would give a less dissonant (and therefore more consonant) sound against the drones.

The blue line assumes that each sound source contributes six equal amplitude harmonics. A good reason for only including six harmonics is that the higher harmonics are closer together in pitch and thus are not so well resolved by the ear [4]. Lines for including up to ten equal amplitude harmonics in the analysis show extra

minima in sensory dissonance being introduced with each additional harmonic.

The shape of the graph for a real bagpipe would depend on the relative amplitude of all the harmonics, which would in turn depend on the instrument, the reeds, the player (including moisture build-up effects and fingerings) and the acoustic of the performance space and listening position. While these factors will affect the relative depth of the minima of sensory dissonance, they will not alter their frequency. This is determined by the simple ratios for coincidence of harmonics of drones against the chanter.

Since each octave corresponds to a frequency ratio of 2, the lowest or fundamental component of the bass drone is a factor of 4 below that of the chanter low A. Labelling the fundamental frequency of low A as  $f$ , the harmonics of the bass drone (when tuned accurately) will thus sound at integer multiples of  $f/4$ , therefore at 0.25, 0.5, 0.75, 1.0, 1.25, 1.5, 1.75 and 2.0 and so on relative to low A.

The horizontal axis on the figure is spaced logarithmically so that equal distance is given to scale steps rather than to harmonics. All five plots show minima indicating clear acoustical reasons for tuning the notes low A, C#, E and high A to achieve coinciding harmonics between chanter and drones if it is desired that dissonance should be minimised. Dissonance is not something that should be minimised at all costs — historically musical taste has dictated preferences for different tunings. A particularly striking example is that the high A has been deliberately tuned flat of the true octave ratio of 2 by some players in order “not to lose the note in the drones” [2].

The line including six harmonics in the analysis also has broad, shallow dissonance minima close to the low G and B pitches, and a single broad minima covering the region including F# and high G. Interestingly, the pitch D is shown to be relatively dissonant due to the fifth harmonic of the bass drone (sounding around C#) lying close enough (around 40 Hz away for typical playing frequencies) to clash with the fundamental frequency of the chanter. A sharper pitch for D would reduce the extent

# scale and sensory dissonance

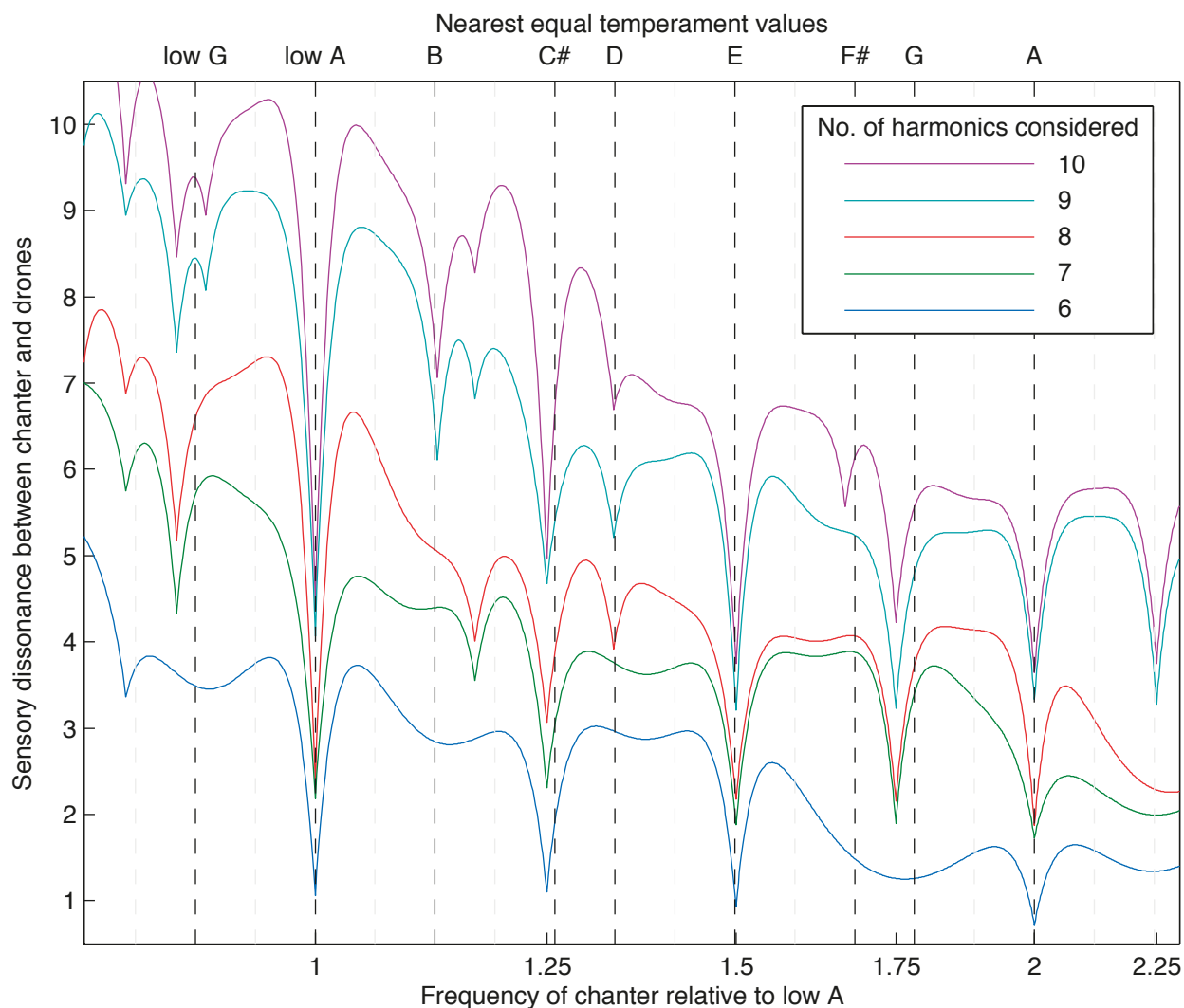


Figure 1. Theoretical plots of sensory dissonance across the range of the chanter, taking into consideration equal amplitude harmonics for bass drone, tenor drone and chanter spectra.

of this clash. Analysis by Brown of the late 17th century chanter of Iain Dall MacKay shows that the D was “colourful”, or sharp of the interval that would be expected from modern instruments by approximately 20 cents[5]. Interestingly this tuning was common until around the 1950s[6].

## Notes of the Pipe Scale

IT is helpful to set out the implications of sensory dissonance for each note in the bagpipe scale in turn, from lowest pitch to highest. In doing so, I will refer to the cent scale in which an equally tempered semitone is divided into 100 cents. The headings for the different notes

in the pipe scale are labelled low G, low A, B, C, D, E, F, high G and high A as is standard in material written by and for pipers, but it should be noted that those labelled C and F are tuned closer to the equally tempered pitches C# and F# respectively (allowing the A Mixolydian mode to sound rather than the A Aeolian mode). In addition to this, the pitch standard for the definition of A has changed over the years to be increasingly sharp of concert pitch.

## Low G Note

WHEN seven harmonics are included in the analysis, a dissonance minimum appears corresponding to a low G tuned 31 cents flat of

the equally tempered value. This is relatively consonant because the second harmonic of the chanter matches the seventh harmonic of the bass drone. When nine harmonics are included, the ninth harmonic of the tenor drones matches the fifth harmonic of the chanter to give a small dip in dissonance at a value 18 cents sharp of an equally tempered low G. These two options for a more consonant low G correspond to the frequency ratios 7/8 and 9/10 (i.e. the frequency of low G over the frequency of low A). It is possible that the preference for one or other tuning may depend on the relative amplitude of the seventh and ninth harmonics in the drone spectra.

### Low A Note

THE first harmonic of the chanter (its fundamental frequency) matches the fourth harmonic of the bass drone and the second harmonic of the tenor drones at the position marked 1.0 on the graph.

### B Note

IF nine harmonics are included in the analysis, then a minimum of sensory dissonance appears where the fourth harmonic of the chanter agrees with the ninth harmonic of the tenor drones. This corresponds to a ratio of  $9/8 = 1.125$  (known as the just intonation ratio for a major second), giving a note 4 cents sharp of an equally tempered B.

### C Note

WHEN the fifth harmonic of the bass drone matches the fundamental of the chanter, a dissonance minimum is obtained at the ratio  $5/4 = 1.25$  or an interval of a pure major 3rd above low A. This corresponds to a pitch 14 cents flat of an equally tempered major 3rd (C sharp). When seven harmonics are included, a weaker minimum occurs at a pitch 33 cents flat of a minor third (C natural). This is due to the third harmonic of the chanter agreeing with the seventh harmonic of the tenor drones, giving a ratio  $7/6$ . The consonance is weaker because of a clash between the fundamental of the chanter and the fifth harmonic of the bass drone (sounding around C#) for this pitch.

### D Note

WHEN including eight harmonics, the third harmonic of the chanter matches the eighth harmonic of the tenor drones to give a dissonance minimum at a ratio of  $4/3 = 1.333$ , or 2 cents flat of an equally tempered D. As with a pure minor third, the consonance of a pure fourth may suffer from it clashing with the fifth harmonic of the bass drone which sounds only a semitone away, at a pure major third.

### E Note

WHEN the chanter sounds a pure fifth above low A, the sixth harmonic of the bass drone and third harmonic of the tenor drones both match the fundamental of the chanter. This occurs at a frequency ratio of  $3/2 = 1.5$ , or 2 cents sharp of an equally tempered E.

### F Note

A minimum appears at  $5/3 = 1.667$  only in the line that includes ten harmonics. This cor-

responds to a pure major 6th, 16 cents flat of an equally tempered F#. This minimum is weak compared to others because the chanter fundamental clashes with the seventh harmonic of the bass drone. Figure 1 shows that the consonance or "sweetness" of F depends on the presence of the tenth harmonic of the tenor drones. If strong, this would ring with the third harmonic of the chanter.

### High G Note

AGREEMENT between the seventh harmonic of the bass drone and the fundamental of the chanter leads to a dissonance minimum for the frequency ratio  $7/4 = 1.75$ . This represents a pitch 31 cents flat of the equally tempered value for high G.

### High A Note

A minimum is located where the fundamental of the chanter matches the fourth harmonic of the tenor drones, which occurs at the ratio 2.0 or a pure octave above low A. This minimum is reinforced if the eighth harmonic of the bass drone, corresponding to the same frequency, is considered.

### Conclusions

THE theoretical plots of sensory dissonance are best viewed as a way of demonstrating why the bagpipe scale is not standardised. Dissonance is a matter of taste but this work sets out the theoretical level of dissonance against drones sounding in the two lower octaves on a solo instrument. Another possible factor (not discussed here) relates to the tuning of the bagpipe scale for achieving satisfactory relative pitches between different chanter notes.

If (and this is a big if) minimum dissonance against the drones is desirable there are clear reasons for optimum harmonic relationships for the notes low A, C#, E, and high A as they rely on only the first six harmonics of the bass and tenor drones against the chanter. For other intervals, the extent to which dissonance against the drones may be avoided is reduced since the harmonics of the drones that are involved lie closer to the limit for separate resolution by the human ear (although under certain acoustical circumstances particular harmonics may be louder than neighbouring harmonics, allowing for improved consonance). That said, the most secure of the intervals for minimising dissonance (requiring the ear to hear the interaction of the seventh harmonics of the bass and tenor drones against the chanter) are those at high G

and low G. The harmonic interval for B requires the ninth harmonic to be perceived.

The pitch F# has a contribution to dissonance associated with its proximity to the seventh harmonic of the bass drone while the harmonic ratio for D, which would be consonant against the chanter low A, may be argued to be the most dissonant of the harmonic intervals discussed when considered against the drones. This is because the fundamental of the chanter D is dissonant against the fifth harmonic of the bass drone roughly a semitone below it (and the second harmonic of the chanter is similarly dissonant against the fifth harmonic of the tenor drones). It is intriguing to speculate that the colourful sharpened D common in Highland bagpipe recordings prior to the 1950s (and present to a decreasing extent thereafter) may have been caused by an attempt to reduce the severity of this clash.

Taste for particular intervals depends on musical acclimatisation in any case and the strength of perception for particular harmonics will depend greatly on individual players and their instruments. Ultimately, this article exposes the complexities involved in basing the tuning of the scale on the dissonance or consonance of the chanter against the drones and is intended to help inform choices related to this issue. Much hinges on the relative loudness of the harmonics that make up the sound colour of the drones and on the player's (and audience's) perception of those harmonic spectra.

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