The Flat Holm Lighthouse Voice - the building as a musical instrument

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The Flat Holm lighthouse stands in a wild soundscape evoked by the ceaseless motion of wind and sea, ebbing and flowing with the seasons. Passing denizens - ships, aircraft, and, above all, seabirds - contribute their hurried and intermittent comment.

A stairway inside the stone masonry leads from an entrance on the rock to the lantern, 75 or so feet above, and is protected by walls over two feet thick, with only the tiniest of sealed windows, quite enough to isolate the hollow core within from the clamour of the world outside.

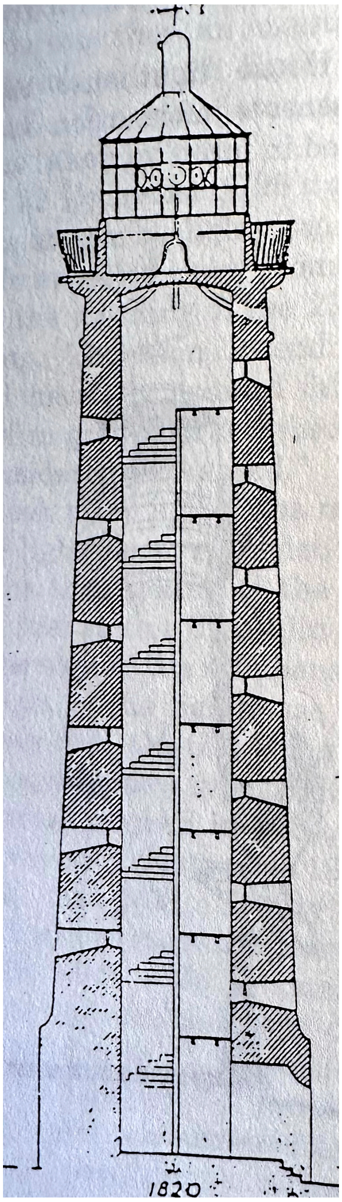
Yet step inside, and instead of the expected silence, the core is found to be generating a distinctive sound of its own. It is singing, basso profundo, with unvarying pitch. It has been doing so continuously for over two hundred years, heard by only the few people who have had the privilege of entering its door.

We encountered the "voice" of the lighthouse on a visit we made with engineers from Trinity House, whose job it is to maintain the light. The continuous low rumble that filled the interior was quite unexpected to us, but unmistakable. It was not the sound of our own activity reflecting back - it sang whether anyone was there to hear it or not. Its singular characteristic was its deep pitch. We were intrigued to know just how deep it was. As a first step, we set up microphones at the foot of the stair and left them to record.

Imagining the lighthouse as a wind instrument

For the lighthouse to have a voice, there must be a continuous source of sound energy to feed it. We cannot be sure what that is, but it is probably the wind, which seemed strong enough on the day of our visit to be a candidate. Looking at its cross-section below, it is easy to see the likeness of the lighthouse to a musical wind instrument - say a giant recorder. If it were such, we could work out its bottom note just as we would with any recorder, from its length.

Imagine how the column of air inside the shaft would be set in motion by the wind. It would oscillate up and down the shaft. Our ears hear such oscillations



as sound, and their frequency as pitch. The entire column can pulse up and down the shaft as one, trapped between its two ends. It is this pattern of motion that gives rise to the bottom note of wind instruments.

There are some well-known formulae for calculating this bottom note. For a standard cylindrical column closed at both ends, its frequency can be found by dividing the column length into the number 170.

The stairwell in the lighthouse is an air column about 22 metres in length. So this rule suggests a bottom note with a frequency of about 8 cycles/sec. That is, the air pulses up and down the shaft 8 times every second.

But there are factors likely to make it pulsate more slowly still. If the entrance to the shaft were leaky enough, it could behave like a column of air open at one end, which would lower its bottom note an octave. And the stair winding up the shaft almost doubles its effective length, also potentially lowering the note an octave.

All these possible notes are well below the lowest a human can hear - they are inaudible. Notes like this are also too low to be detected in our recordings. Yet they exist. If lively enough, they can be felt by the human body. The bottom note we are looking for is lurking in a world of mute vibration. Yet we do have a method for finding from the audible data in our recordings.

The stack of notes above the bottom note

When we look closely at the recording we made, we find that the rumble is really a stack of discrete notes with different pitches. This is not unusual; musical instruments typically produce a stack of notes like this. The pitch we hear for the instrument is the one at the bottom of the stack. So we can find the bottom note of an instrument by measuring the pitch of the lowest note in the stack. But because the bottom note of the lighthouse is inaudible, it will be below the lowest of the notes in the stack we recorded.

The explanation of how sounds of several pitches form in wind instruments is that the simple oscillation made by the bottom note breaks up into segments, simple fractions of the whole, making new patterns of oscillation that fit neatly into the air column. The greater the subdivision, the higher the frequency of the oscillation, and so the higher the pitch of the note. In the lighthouse, these are the patterns most readily activated by the wind, and they are also the notes that resonate when someone plays them - the resonant frequencies.

To illustrate, for the bottom note of 7.8 cycles/second, the pattern of oscillation is for the whole air column to move as one. That pattern might split into halves, or into thirds, or into quarters, and so on. Taken in order, the frequencies of these new patterns are simple multiples of the bottom frequency - twice, three times, four times, making what is known as a harmonic series. The following is the series of frequencies that results:

(1) **7.8** c/s, (2) **15.6** c/s, (3) 23.3, (4) 31.1, (5) 38.9, (6) 46.6, (7) 54.4, (8) 62.2, (9) 69.9, (10) 77.7, (11) 85.5, (12) 93.3, (13) 101.1, (14) 108.8, etc.

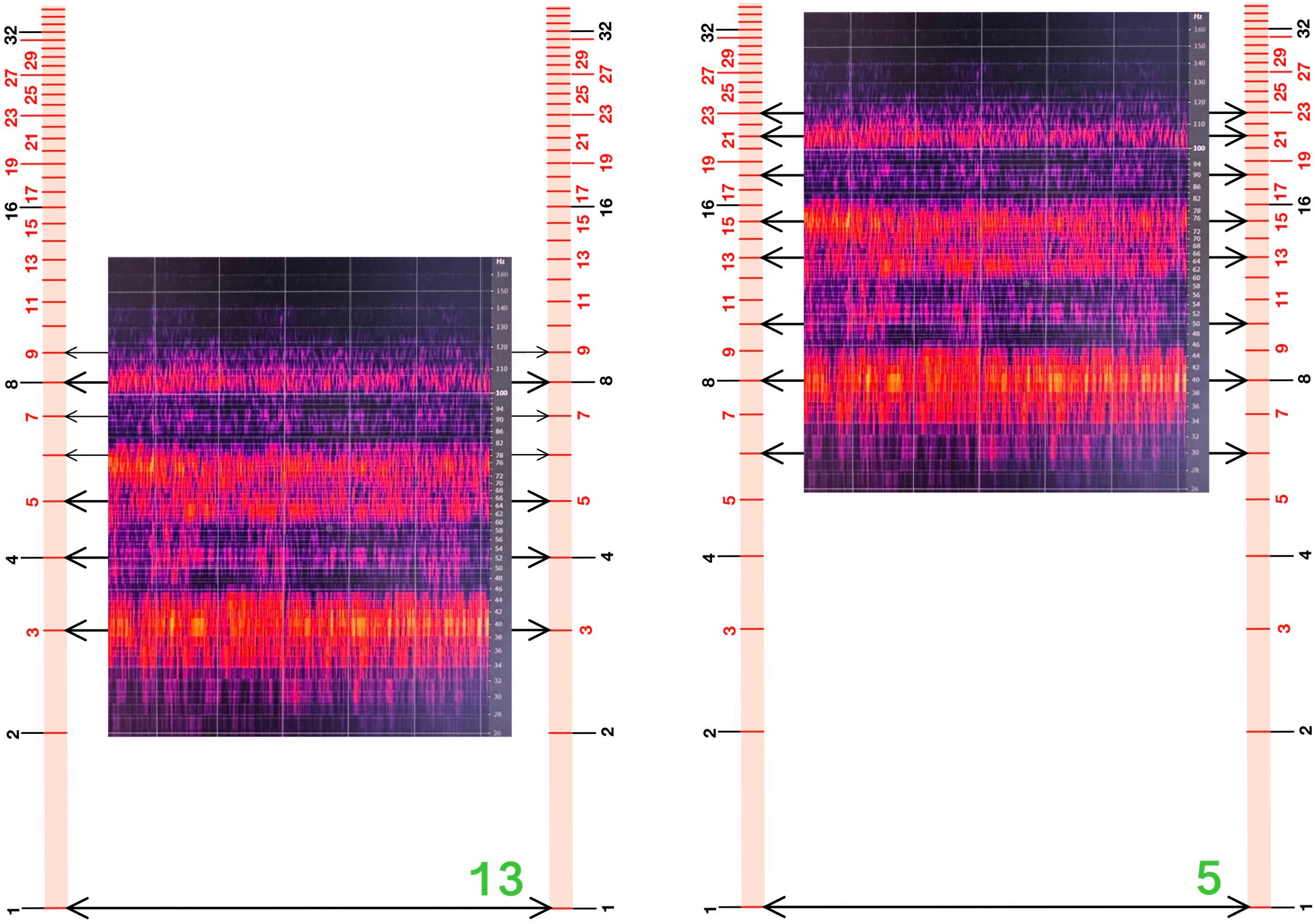
As you see, each of these *harmonics* has the frequency of the bottom note multiplied by its harmonic number (1, 2, 3, etc.). Those below about 20 cycles/second (the ones in bold type) are inaudible to the human ear.

So we can expect the notes we hear in the recording to be a harmonic series rising in multiples from some unknown and inaudible bottom note. Whatever that note is, its upper harmonics (two times its frequency, three times, and so on) should coincide with the notes we hear in our recording. So here is a way of discovering where the bottom note is. We make a guess at its frequency, and so at the whole series of harmonics that goes with it. If we guess correctly, then its harmonics should match the stack of notes in our recording. If we get the guess wrong, the match will be poor.

To illustrate this, we can try the idea out on our current estimate of the bottom note, 7.8 cycles/second. We have just listed Its harmonics above. When we compare these with the resonant notes in the recording, we find some match between them, but not a close one. The lowest two notes in the recording line up well with harmonics 4 and 5, but there are plenty that don't. There are notes in the recording which don't relate well to any harmonic, and there are harmonics that don't correspond to any notes at all. Can we do better?

There is a caveat. In practice, we can only expect the notes we hear to approximate an ideal harmonic series based on idealised forms. The lighthouse air column is not a simple closed-ended cylinder. Its performance is complicated by the staircase, by air leakage at the bottom and top, by the window cavities, and so on. Such deviations from the ideal affect which harmonics are actually produced. Some may be stronger than others, some may be absent (for example, in a column open at one end, only the odd-numbered harmonics sound), and any of them may have shifted frequencies.

Even so, this method does let us find a bottom note whose harmonic series is a better match for the recording. Here are the steps.



Using the harmonic series to find the bottom note

In the two figures above, the rectangle with a black background (it's the same in both figures) is a graphic display of our recording, known as a spectrogram. The red bands show the stack of notes we earlier referred to in our recording: those with a higher pitch are higher up, and the louder notes are brighter. There is a scale of frequencies on the right-hand border of the spectrogram, which is unlikely to be legible in the reproduction, but counts from 26 c/s at the bottom to 160 c/s at the top, all within the audible range. The frequencies of the louder resonant notes that were heard are centred on around 39, 62, 74 and 105 c/s. The dominant low frequency at around 39 c/s is the one that interests us most, and is in fact spread out to cover a broad band of frequency.

Additionally, on either side of the spectrogram, a theoretical harmonic series is drawn as a vertical scale with red spacers. It is labelled with the harmonic numbers, 1, 2, 3, 4, etc. Both the spectrogram and the harmonic series use the same logarithmic scale, such that octaves have equal lengths on both, regardless of the starting point. The same applies to any other musical interval.

In practice. the method is to slide the spectrogram up or down between the harmonic scales until the observed resonant frequencies line up well with the harmonic series. Then the first harmonic ('1' on the harmonic scale) will be alongside the bottom note of the lighthouse, or where that would be if the spectrogram were extended downwards.

As you slide the spectrogram down, the first harmonic aligns with progressively higher frequencies. If the spectrogram is taken too low, the resonances found above the first harmonic are too closely packed to find enough harmonics to align with. The position shown above left is the lowest for which almost all the resonant frequencies can find a match. Then the bottom note of the lighthouse (alongside the first harmonic} is ***13 c/s***. Because the spectrogram cannot be lowered further, the lowest audible band, around 39 c/s, cannot be below the third harmonic (and so cannot be the bottom note). 13 c/s sets an upper limit for the bottom note, putting it firmly below the audible threshold.

Possible lower bottom notes were sought by moving the spectrogram upwards from there in steps that align the 39 c/s band with successive harmonics. Each step leaves some observed frequencies unaccounted for, until this lowest band reaches the 8th harmonic. Then the alignment is good, or at least acceptable, at all frequencies. There are potential harmonics in the series that are not observed, but never more than two in a row. This is the position shown in the figure on the right above. The bottom note is then about ***5 c/s***.

Taking the spectrogram higher still (and the bottom note lower) moves it into regions where the harmonics are ever more closely spaced. It becomes increasingly easy to get a match, but by the same token even bigger clusters of harmonics become redundant. Matches become so random that the test loses its value. So 5 c/s is the lowest bottom note the method can safely attest.

The idea of a bottom note as low as 5 c/s seems realistic. For example, taking the staircase into account, the overall path length of the air column becomes 39 m. A closed tube of that length would have a bottom note close to 4.5 c/s.

Summary

The lighthouse has an internal voice with a very low pitch - but how low?

Basic musical theory, using the dimensions of the interior, shows that its pitch could quite credibly lie below the audible range. But the shape of the interior is too complicated to make a reliable estimate of the actual frequency in this way. A simple graphic analysis, looking for a match between the notes in the recording and a harmonic series, confirms that the bottom note must be below the threshold of hearing. The best fit we could find attributes the bottom note of the lighthouse to air sloshing up and down the shaft at the syrupy frequency of five cycles/second, which is two octaves below the audible limit.

We now have apparatus that can detect and measure the true frequency directly. It could also be sought from acoustic modelling of the lighthouse interior. Enough has been done here to draw attention to this phenomenon. If it is caused in the way we suppose, we anticipate that similar voices could be found in other lighthouses around the world, with their own pitch and tonality.