

# At the Faintest Audible Sound at One Kilohertz, the Air Moves Together by Less Than the Radius of a Hydrogen Atom

— that displacement is of the order of a ten-thousandth of the path a molecule travels between collisions, and sound is a slight shared bias in the average of molecules flying about at random — the separator is whether the shared motion of many molecules is looked at, or the motion of one — [Paper 920]

Yuuki YAMAGISHI (山岸 勇輝)

Yamagishi Complexity Torus Lab, Japan

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— *From thinking to syncing.* —

## Abstract

Sound is a fluctuation of air pressure, and it is also the air moving back and forth together. This paper counts how far and how fast the air moves together in a sound at the reference pressure of 20  $\mu\text{Pa}$  (rms), varying frequency and pressure, and compares this with the size of an atom and with the random motion of molecules (heat). No new theorem or law is claimed. First, at one kilohertz the air moves together by less than the radius of a hydrogen atom: in air at 20 degrees Celsius (characteristic impedance 413.2128 Pa s/m), the rms displacement at 20  $\mu\text{Pa}$  and 1 kHz is  $7.7033 \times 10^{-12}$  m, **0.145571** times the radius of a hydrogen atom (the Bohr radius) (Section 2). Second, that is of the order of a ten-thousandth of the path a molecule travels between collisions: the mean free path from representative values is  $6.5673 \times 10^{-8}$  m, and the displacement is  $1.1730 \times 10^{-4}$  times it. The shared velocity is  $4.8401 \times 10^{-8}$  m/s,  $1.0457 \times 10^{-10}$  times the mean molecular speed of 462.8687 m/s (Section 2). Third, at the same pressure, a lower sound moves the air further: displacement is inversely proportional to frequency:  $3.8516 \times 10^{-10}$  m at 20 Hz (7.278559 Bohr radii) and  $3.8516 \times 10^{-13}$  m at 20 kHz. Displacement found by integrating the velocity matched the formula at a ratio of 1.000000000 (Section 3). Fourth, raising the pressure a millionfold moves the air only a million times further: at 120 dB (20 Pa) and 1 kHz the displacement is  $7.7033 \times 10^{-6}$  m, with intensity  $10^{12}$  times and displacement  $10^6$  times as large (Section 3). Fifth, the separator is whether the shared motion of many molecules is looked at, or the motion of one: a single molecule flies at random at hundreds of metres per second and changes direction every mean free path. An audible sound is a slight shared bias in their average, and the extent of the shared motion is far smaller than the path of one molecule (Section 4). **Keywords:** sound pressure, particle velocity, air displacement, mean free path, Bohr radius, characteristic impedance.

Scope of this paper (scope note): No new theorem or law is claimed: the relations among pressure, particle velocity and displacement in a plane sound wave, the characteristic impedance of air, and the mean free path and mean speed of kinetic theory are all standard. Hearing is not discussed: how the ear perceives, and how the faintest audible pressure changes with frequency, are not treated. 20  $\mu\text{Pa}$  is a reference value and is applied at every frequency for counting. The eardrum is not computed. What is counted is the air displacement of a plane wave in free space, not the displacement inside the ear. The values are representative: air density 1.204 kg per cubic metre, sound speed 343.2 m/s, temperature 293.15 K and effective molecular diameter  $3.7 \times 10^{-10}$  m are used. Noise is not tied to the threshold. It is not said that the thermal motion of molecules sets the faintest audible sound. The sizes of shared and random motion are only set side by side. Relation to earlier papers: Paper 276 showed that the decibel is a ratio, not a quantity. Here the reference of that ratio, 20  $\mu\text{Pa}$ , is turned back into quantities of length and speed by counting how far it moves the air. Paper 456 showed that doubling the distance is not enough to halve loudness. Here it is not distance but frequency and pressure that are varied, counting how far the air moves. What is added: comparing the air displacement at the reference pressure with the radius of an atom, comparing that displacement and velocity with the mean free path and the mean molecular speed, confirming by integrating the velocity that displacement is inversely proportional to frequency, setting down the displacement at 120 dB, and placing the separator on “shared motion, or the motion of one molecule”.

## 1. Notation and the Question

Setting: with rms pressure  $p$  of a plane sound wave, air density  $\rho$ , sound speed  $c$  and frequency  $f$ , the rms velocity  $u$  and displacement  $\xi$  of the air moving together are:

$$u = \frac{p}{\rho c}, \quad \xi = \frac{u}{2\pi f} = \frac{p}{\rho c 2\pi f}$$

The random motion of molecules is expressed by the kinetic-theory mean free path  $\ell = k_B T / (\sqrt{2} \pi d^2 P)$  and mean speed  $\bar{v} = \sqrt{8 k_B T / \pi m}$ . The check finds the displacement not only from the formula but also by integrating a sinusoidal velocity over half a period.

Question: how far does the air move together in the faintest audible sound, and how does that compare with the motion of a single molecule?

## 2. Motion at the Reference Pressure

Computation 2.1: with representative values (density 1.204 kg per cubic metre, sound speed 343.2 m/s, 293.15 K, effective molecular diameter  $3.7 \times 10^{-10}$  m, Bohr radius  $5.29177 \times 10^{-11}$  m):

| quantity                           | value                                                                                                |
|------------------------------------|------------------------------------------------------------------------------------------------------|
| characteristic impedance $\rho c$  | <b>413.2128</b> Pa s/m                                                                               |
| intensity at <b>20</b> $\mu$ Pa    | <b><math>9.6802 \times 10^{-13}</math></b> W per sq m ( <b>0.968024</b> of the $10^{-12}$ reference) |
| shared velocity                    | <b><math>4.8401 \times 10^{-8}</math></b> m/s                                                        |
| displacement at <b>1</b> kHz (rms) | <b><math>7.7033 \times 10^{-12}</math></b> m (peak <b><math>1.0894 \times 10^{-11}</math></b> m)     |
| mean free path                     | <b><math>6.5673 \times 10^{-8}</math></b> m                                                          |
| mean molecular speed               | <b>462.8687</b> m/s                                                                                  |

The displacement at 1 kHz is **0.145571** Bohr radii and  $1.1730 \times 10^{-4}$  mean free paths, and the shared velocity is  $1.0457 \times 10^{-10}$  of the mean molecular speed.

**Observation 2.2**

at the faintest audible sound at one kilohertz, the air moves together by less than the radius of a hydrogen atom. That extent is of the order of a ten-thousandth of the path a molecule travels between collisions, and the velocity of the order of a ten-billionth of the molecular speed: within the motion of a single molecule, the motion of the sound cannot be seen.

### 3. Varying Frequency and Pressure

Computation 3.1: frequency varied at 20  $\mu$ Pa.

| frequency     | rms displacement (m)                       | in Bohr radii   | in mean free paths                        |
|---------------|--------------------------------------------|-----------------|-------------------------------------------|
| <b>20</b> Hz  | <b><math>3.8516 \times 10^{-10}</math></b> | <b>7.278559</b> | <b><math>5.8649 \times 10^{-3}</math></b> |
| <b>100</b> Hz | <b><math>7.7033 \times 10^{-11}</math></b> | <b>1.455712</b> | <b><math>1.1730 \times 10^{-3}</math></b> |
| <b>1</b> kHz  | <b><math>7.7033 \times 10^{-12}</math></b> | <b>0.145571</b> | <b><math>1.1730 \times 10^{-4}</math></b> |
| <b>4</b> kHz  | <b><math>1.9258 \times 10^{-12}</math></b> | <b>0.036393</b> | <b><math>2.9324 \times 10^{-5}</math></b> |
| <b>20</b> kHz | <b><math>3.8516 \times 10^{-13}</math></b> | <b>0.007279</b> | <b><math>5.8649 \times 10^{-6}</math></b> |

The displacement from integrating a sinusoidal velocity over half a period matched the formula at a ratio of 1.000000000 at 20 Hz, 1 kHz and 20 kHz.

Computation 3.2: pressure varied at 1 kHz.

| sound pressure level | pressure (Pa)           | displacement (m)         |
|----------------------|-------------------------|--------------------------|
| 0 dB                 | $2.0000 \times 10^{-5}$ | $7.7033 \times 10^{-12}$ |
| 60 dB                | $2.0000 \times 10^{-2}$ | $7.7033 \times 10^{-9}$  |
| 120 dB               | $2.0000 \times 10^1$    | $7.7033 \times 10^{-6}$  |

At 120 dB the intensity ratio is  $10^{12}$  and the displacement ratio  $10^6$ , and the square root of the intensity ratio matched the displacement ratio.

**Observation 3.3**  
  
at the same pressure, a lower sound moves the air further. Displacement is inversely proportional to frequency, so 20  $\mu$ Pa at 20 Hz gives an extent of 7.278559 Bohr radii. That is still  $5.8649 \times 10^{-3}$  mean free paths, and even at 120 dB the extent at 1 kHz stays at  $7.7033 \times 10^{-6}$  m.

#### 4. The Separator

**Observation 4.1**  
  
the separator is whether the shared motion of many molecules is looked at, or the motion of one. A single molecule flies at random at a mean 462.8687 m/s and changes direction every  $6.5673 \times 10^{-8}$  m: sound is a slight shared bias in their average; at the faintest audible sound the extent of that bias is smaller than the radius of an atom, and its velocity  $1.0457 \times 10^{-10}$  of the molecular speed.

### Observation 4.2

what is not said. How the ear perceives, how the faintest audible pressure varies with frequency, the motion of the eardrum, and whether thermal noise sets the threshold are not treated. What is shown is how small the extent and velocity of the air's shared motion at the reference pressure are, compared with atoms and molecular motion.

## 5. Roll Call and Closing

1.  $u = p/\rho c$ ,  $\xi = u/2\pi f$  (Section 1): **shared motion.**
2.  $7.7033 \times 10^{-12}$  m at 1 kHz, **0.145571 Bohr radii** (Computation 2.1): **smaller than an atom's radius.**
3.  $1.1730 \times 10^{-4}$  mean free paths (Computation 2.1): **order of a ten-thousandth.**
4. velocity  $1.0457 \times 10^{-10}$  of the molecular speed (Computation 2.1): **a slight bias.**
5. **7.278559 Bohr radii at 20 Hz** (Computation 3.1): **inversely proportional to frequency.**
6.  $7.7033 \times 10^{-6}$  m at 120 dB (Computation 3.2): **intensity  $10^{12}$ , displacement  $10^6$ .**
7. **shared motion, or one molecule** (Observation 4.1): **the separator; Papers 276 and 456.**

**Closing:** At the faintest audible sound at one kilohertz, the air moves together by less than the radius of a hydrogen atom. The displacement at 20  $\mu$ Pa and 1 kHz was  $7.7033 \times 10^{-12}$  m, 0.145571 Bohr radii and  $1.1730 \times 10^{-4}$  mean free paths: the shared velocity was  $1.0457 \times 10^{-10}$  of the mean molecular speed; displacement is inversely proportional to frequency, and even at 120 dB it stayed at  $7.7033 \times 10^{-6}$  m at 1 kHz. Sound is a slight shared bias in the average of molecules flying about at random: the separator is whether the shared motion of many molecules is looked at, or the motion of one. Placed among the earlier papers: the reference of the decibel, treated as a ratio in Paper 276, was turned back into quantities of length and speed, and the sound moved by distance in Paper 456 was moved by frequency and pressure. To be honest: nothing is said about how the ear works. How far the reference sound moves the air, and no further.

## References

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**Yuuki YAMAGISHI (山岸 勇輝)**

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