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**Effects of Carbon Dioxide on the Speed of Sound from a Pipe Organ**

**Abstract**

How do environmental factors affect the speed at which sound waves travel in gasses? The way in which sound travels is dependent on the media within which it travels. In gasses, characteristics such as the molecular composition and temperature and moisture content can alter the frequency, or wave motion, of sound waves.1 Musical instruments, such as pipe organs, depend on sound moving through air at certain speeds to produce desired musical notes at set pitches. Pipe organs particularly depend on their localized environment, as they often reside in large church buildings. Pipe organs are typically tuned by an organist while the building is empty then played in performance for an audience, whose presence introduces increased temperature, CO2, and water vapour. Do changes in the environmental conditions in organs’ buildings affect the pitch of the notes? This investigation focuses specifically on examining the change in pitch from CO2 concentration. Using equations for frequency from CO2 concentration, I will compute predicted pitch and compare measured pitch to see whether, and how much, CO2 concentration affects pitch.

**Introduction**

Because sound travels via the movement of air, the characteristics and composition of air affect the speed of sound. Therefore, studying the effects of atmospheric conditions such as molecular composition of air can provide insights into the nature of sound travelling in an area.1 This directly applies to musical instrumentation construction, management, and use. Many mechanical instruments are adjusted or tuned to emit certain pitches, or the frequencies of sound waves propagated from the instrument. Knowledge of ideal tuning depends on knowledge of the rate at which the sound waves will propagate through the instruments. Since sound waves are affected by the media within which they travel, location and environmental conditions surrounding instruments greatly affects their sound **(CITE).** Cramer provides documentation of the relationship between changes of sound speed and air characteristics such as: temperature, relative humidity (RH), and carbon dioxide concentration.2 It has been seen that frequency of sound waves has a calculable relationship to these environmental factors. These calculations can provide insight into how much is musical pitch affected by changing characteristics of ambient air.

We can examine change in pitch from environment with musical instruments by using previously calculated relationships between air characteristics and speed of sound outcomes. Mechanical pipe organs are especially vulnerable to changes in their environment because they are often located in large, heterogeneous buildings, with large audiences, which impact air characteristics.3 Additionally, the pipe and bellow system moves air throughout different parts of their chambers creating mixed air effects. If a muted tone is desired, shades are closed reducing the flow of air between sections of organ pipes. How much do these situational variables affect tuning of some pipes relative to others making the instrument sound off key? Traditionally, tuning adjustments on pipe organs are completed when the church is empty, however organs are typically played when the building is filled with an audience. Along with an increase in temperature and water vapour, the presence of people and the human respiratory process produces significant amounts of CO2, which is a heavier molecule than air, mostly comprised of N2 and O2. Therefore, its presence affects calculations of molar mass of air, particularly with high levels of air moisture, as is caused by breathing.4, 5 With pipe organs the effects of human presence on air quality is especially high due to the closed environment organs are located in. How much does the frequency of the notes change with environmental differences between conditions during tuning versus during performance? Additionally, will the tuning of different sections of the organ change in relation to others, based on regional differences? This study looks to examine carbon dioxide concentration in the chapel containing a mechanical organ to examine the relationship between CO2 and speed of sound propagated from movement of air through organ pipes.

**Methods**

This study will use data that charts concentration of carbon dioxide (CO2) and pitch of notes played on the pipe organ at the church of St. Paul’s School in Concord, NH USA, collected by Dr. Ian Hoffman. Computational analysis of the data will make use of the mathematical relationship between CO2 concentration and changes to the speed of sound, as described by Cramer.2 The complete project repository can be found here: <https://github.com/taliamo/Final_Project>

The data was collected at St. Paul’s School in 2010. Data of the frequency of sound produced by notes on the pipe organ were logged by hand. These were taken while the church was empty of visitors or filling up or emptying out. Environmental characteristics data was collected and recorded using Onset® U12-03 and Telaire 7001 HOBO® data logging devices for temperature and relative humidity (RH) and for CO2 (ppm) readings, respectively. The environmental data was initially converted from .hobo to .csv files using HOBOWare® for analysis in Python. Using Python version 3.4.0, data will be arranged for computation, quantitative analysis, calculation of statistical significance, and formation of graphical presentations. Pandas, Numpy and Matplotlib Python libraries **(WHICH VERSION??)** are used for computation and plotting operations. Two types of scripts are used, one for processing pitch and one for environmental data.

The data is first wrangled and cleaned in Python to create two data frames for each type; one to house environmental data and another type for pitch measurements. The environmental data files are kept for certain locations and consist of date and time, temperature, relative humidity, and CO2. The pitch data files consist of date and time, division of the pipe whose note is played, musical note played, and frequency values from multiple samplings taken at the same date time value. A mean frequency value for each time stamp was generated, as well as standard deviation.

In the environmental dataframes, CO2 data are run through the “cramer” function to generate values for calculated pitch, as per Cramer’s equation for frequency of sound from environmental characteristics.2 Here, a modified version of the equation is used to isolate for CO2 concentration, apart from temperature and humidity. The plotted points of measured pitch come from the average frequency data. To compare measured and calculated pitch values, documented pitches and environmental data are grouped by area in the chapel. Later, measured pitch points can be plotted over top of calculated pitch values. This comparison allows for examination of the correlation between change in calculated and measured frequency of sound from a note on the pipe organ. Unfortunately, data used for this project does not have overlapping timeframes for samples of measured pitch and of CO2 (which are used to generate expected pitch). Therefore, making a graphical comparison between measured and calculated pitch is not feasible. The two variables are not comparable because the hypothesis looks to examine how pitch changes as affected by CO2 concentration. Therefore, it is necessary to compare pitch changes at the same time and date that change in CO2 concentration is also being examined.

**Results**

The script to plot CO2, calculated frequency, and measured frequency did not succeed in Shell script form. Additionally, no comparisons could be made between calculated and measured pitch, due to the lack of time-overlapping data, as mentioned above. However, computational results do show the change in CO2 concentration in the air of the church over time, through the number of samples taken every 2 minutes (Figure 2). Here, samples of the c5 (middle-high C note on the pipe organ) were taken over three days. Pitch of the note changes from ~ 423.9 Hz to ~ 524.7 Hz.

Additionally, CO2 concentration varies greatly, from ~ 450ppm to ~ 1350ppm at the peak of the highest spike (Figure 1). Due to the times of those spikes and qualitative notes documented alongside the data collection, we can say that the spikes are indeed caused by the presence of an audience in the church.

**Fig 1.** CO2 concentration over sample number. Samples are taken 2 minutes apart from one another. This figure displays CO2 sampled inside the pipe organ, near the choir division.

**Fig 2.** Change in pitch over time. Samples of the c5 note in the choir division of the pipe organ in St. Paul’s School church were taken over 3 days (April 13th, 16th, and 17th).

Because measured sound frequency (Figure 2) and measured CO2 concentration (Figure 1), cannot be compared against one another because of the lack of overlap of timing, statistical analysis of the rate of change of the two variables cannot be performed.

**Discussion**

This study’s major limitation is the comparability of measured and calculated pitch, or sound frequency. The analysis depends on relative pitch, not absolute values, since each organ is tuned slightly differently so that one middle C note on one instrument may be different in another location. Therefore, this study depends on comparing data from the same location at the same time. Since overlapping time for measured and calculated pitch (from measured CO2 data) was not available, limited conclusions on the affect of CO2 concentration on sound frequency can be made.

Interesting observations can be made about the affect of human population in the church and change in CO2, which—based on Cramer’s equation—suggest a change in pitch from the introduction of additional heat, CO2, and water vapour from human bodies and breath.2 In Figure 1, the spikes of CO2 concentration can be attributed to people entering the church. These spikes follow similar trends, which is in keeping with the scheduling of the church. Members of the St. Paul’s School community attend regular prayer services, as well as special performances. Most of the audience enters the space within **a few minutes** of the rest of the attendees, and leave at the same rate, causing rapid change in CO2 concentration. **Figure 2** documents that pitch of organ notes do really change over time. The c5 note values plotted in Figure 2 span five days—not enough time for an organ to alter its tuning in the same way that pipe organs, and other instruments, periodically need adjusting. Using statistical tools to quantify the relationship between CO2 and change in pitch would provide deeper insight into the impact of air quality on sound.

Future study could provide insight into a predicted pitch value, which can span any timeframe, so that measured pitch can be appropriately plotted and compared alongside a curve of calculated pitch. Ultimately, expanding the study to look at the effects of environmental variables, such as temperature, would provide more scientifically meaningful insight into how pitch changes from changes in air characteristics. To do this, useful metadata consists of temperature and RH measurements taken at the same time, with the same sensors, in the same locations as CO2 concentration, as well as temperature readings outside the chapel. Additional meteorological information from nearby weather stations could be used to examine temperature and pressure changes. By continuing to study environmentally caused changes in the speed of sound produced by pipe organs, better tuning and construction can be employed. More broadly, this can provide insight into how molecular composition and temperature qualities can affect sound travel in partially enclosed environments.

**Works Cited**

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4 A. Picard, R. S. Davis, M. Glaser, and K. Fujii. “Revised formula for the density of moist air (CIPM-2007)”. Meterologia ; 45; 149-155 (2008).

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**OUTLINE**

Abstract:

-introduce main ideas,

-looking at changes in pitch, which is the frequency of sound creating a certain note, as CO2 changes

-will use an equation for frequency from CO2 to predict pitch then look at measured pitch CHANGE (not absolutes)

Introduction:

-air quality affecting sound speed

-pipe organ’s dependency on air quality (location, big building, audiences)

-audience influence of air quality

-lack of other studies ??

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Methods:

-Software used,

-Wrangling (creation of two dataframes),

-calculating median/st error for pitch,

-plotting CO2 vs. time,

-plotting predicted pitch based on CO2 (same plot),

-overlaying measured pitch measurement points on calculated line.

-stats test for significance of correlation relationship

Results:

-statistical significance of the correlation between change in CO2 and change in pitch (expected versus measured pitch at times of high and low CO2 concentration)

Discussion:

-This is the correlation I’ve found

-Further studies include comparing temp and molarity of water from relative humidity

-outdoor temperature

-air pressure

-calculating for expansion coefficient of the lead pipes

-measuring pitch while there is an audience there, for more regular and consistently-timed observed\_pitch values

Plots of CO2 over time, show spikes where people enter and leave the space (TRACK THIS WITH SUNDAY/MORNING SERVICE TIMES).

We can see how the measured pitch points overlay with the curve of calculated pitch—and see how much they change

This stats test shows the correlation of change in CO2 and change in measured pitch (relationship between measured and calculated pitch)

The calculated pitch is not true pitch values, but we’re just looking at change in calculated pitch, so that’s OK.

The peaks of the calc\_freq plot line don’t spike as high as the CO2. What’s up with that?