# Problem of Placing the Organ Pipes on the Windchest

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**Abstract**

This paper presents research showing the problem occurring in the construction of a pipe organ, related to the placement of the organ pipes on the windchest. The close location of the organ pipes to each other influences the parameters of the sound generated by the pipes. It causes an intonation problem, namely the detuning of the organ pipes if they are located too close to each other on the windchest. The presented measurements show the influence of a distance between pipes of various types on basic sound parameters, such as frequency or volume level. The research carried out shows that in extreme cases the detuning reaches a temperate halftone. This has undoubtedly an impact on the tuning of organ pipes, especially in the case of a table organ or pipe organ built in a small space. In the future, the outcomes of the presented research can be applied in the windchest design.

***Keywords:*** pipe organ, windchest, organ pipe distance

## 1. Introduction

An organ is a musical instrument built of many pipes, placed on a windchest, i.e. a device used to distribute air between particular pipes [1]. While making the instrument, there is not much space for a large distance between these numerous pipes on a windchest. In the small instruments, e.g., table organs, the dimensions of the windchest are relatively small. As a consequence, intonation problems occur because the neighbouring pipes can influence each other's sound. The main reason for this kind of issues is the way of sound generation, because the necessary condition of proper working of the organ pipe (i.e. generating the sound) is a turbulent flow through the so-called mouth of the pipe [1]. Changes in the flow significantly affect the sound parameters.

This paper presents research on the impact of placing organ pipes (on the windchest) on the basic sound parameters. This problem is a critical issue from the viewpoint of organbuilders, as well as musicians playing small organs. The final goal of this research is to create a model of the behaviour of organ pipes during tuning and intonation.

The results presented in this paper are new in the area of research on the acoustics of pipe organs. Previous publications relate primarily to the work of the organ pipe as a sound source without taking into account its environment [2, 3, 5, 6, 8-10].

## 2. Measurements

The presented research was carried out on the intonation table in an organbuilder's workshop. The air pressure in the windchest was set to 67 mm water gauge. In the organbuilding community, the measurement of relative pressure is commonly applied, using the u-tube manometer filled with water. The air temperature in the workshop was 19ºC.

We performed the sound measurements using the sound recording at various distances from the obstacle. For each distance, the measurement was performed at least five times. The obstacles were set at distances from 0 mm to 80 mm, in 5 mm steps. At a distance equal to or greater than 80 mm, we did not notice changes in the parameters of the recorded signal.

a) b)

Figure 1. Measuring point and sample measurement for Bourdon 8-foot:
a) without obstacles, and b) with an obstacle

The measurements (Figure 1) were made for labial pipes representing various types: Principal 4-foot (open, metal, 75% tin and 25% lead, English bay leaf mouth with 29.4 mm width, 37.9 mm internal diameter, 530 mm wavelenght, the theoretical frequency: 323.16 Hz), Bourdon 8-foot (open, oakwood, external mouth with 41.1 mm width, 41.9 x 51.9 mm internal dimensions, 580 mm wavelenght, the theoretical frequency: 295.3 Hz) and Bourdon 16-foot (stopped, oakwood, external mouth with 41.8 mm width, 42.4 x 54.5 mm internal dimensions, 590 mm wavelenght, the theoretical frequency: 145.15 Hz). They are basic voices in almost every pipe organ, so we consider them representative for our research.

The sound was recorded using two measuring microphones at the same time with omnidirectional characteristics, the sensitivity of 10 mV/Pa, and an equivalent noise level of 20 dBA. The microphone no. 1 was positioned at a distance of 58 mm from the top of the pipe, and microphone no. 2 at a distance of 49 mm from the mouth of the pipe. During the recordings, Class 1 acoustic calibrator was also used (1 kHz, 94 dB).

## 3. Analysis and results

During the measurements, significant changes in the pitch of the pipe were noticed in the case of a small distance between the pipe mouth and the obstacle. As a consequence, the decision was made to analyse the following sound parameters: the fundamental frequency ($F_0$) depending on the distance of the obstacle from the mouth of the pipe, and the sound level of the first harmonic. The frequency analysis was performed in two stages. In the first stage, the fundamental frequency was found using the FFT [4] in GNU Octave programming language. The accuracy of the transform was 0.8 Hz. Due to the insufficient accuracy of this transform, the DTFT [4] in a program written by the authors in the Java environment was used in the next stage. The DTFT calculations were made in the range of $F_0$ ±5 Hz, for $F_0$ calculated in the first stage. The assumed DTFT accuracy was 0.01 Hz. Due to the usage of the calibration signal, the first harmonic's sound level analysis for the recordings was also performed (Figure 3).

The measurement uncertainty was calculated as a standard deviation from the obtained results. For the $F_0$ frequency, the following formula was used:

$$\sigma_{F_0} = \sqrt{\frac{1}{N-1}\sum_{k=1}^{N}(F_0[k] - \mu_{F_0})^2} \tag{1}$$

where: $\mu_{F_0}$ - average $F_0$, $N$ - number of measurements, $k$ - measurement number.

Analogously to (1), the measurement uncertainty of the first harmonic's sound level was also calculated. Tables 1-3 present the results of the analysis. The dependencies between the $F_0$ frequency of the pipe and the distance from the obstacle are presented in Figure 2.

Distances between sounds in the equal temperament are described by intervals. Interval is the difference between two sounds. Cent is a logarithmic unit of interval measurement [7]. For each interval, the difference $W_{F_0}$ between the measured sound and the sound without the obstacle was calculated using the following formula:

$$W_{F_0} = 1200 \cdot \log_2\left(\frac{F_0(x)}{F_0(80)}\right) \tag{2}$$

where $x$ is the distance from the obstacle.

Table 1. The list of measurements for the organ pipe - Bourdon 16-foot stopped, c sharp

| x | $\mu_{F0}$ | $\sigma_{F0}$ | $W_{F0}$ | Microphone no. 1 | | Microphone no. 2 | |
|---|---|---|---|---|---|---|---|
| | | | | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ |
| [mm] | [Hz] | | [cent] | [dB] | | | |
| 0 | 131.44 | 0.02 | -99.8 | 86.32 | 0.03 | 103.46 | 0.02 |
| 5 | 135.12 | 0.01 | -52.0 | 87.86 | 0.03 | 105.51 | 0.03 |
| 10 | 136.95 | 0.01 | -28.7 | 89.32 | 0.02 | 105.61 | 0.03 |
| 15 | 137.82 | 0.02 | -17.7 | 88.91 | 0.03 | 105.88 | 0.02 |
| 20 | 138.30 | 0.02 | -11.7 | 88.30 | 0.06 | 106.02 | 0.05 |
| 25 | 138.60 | 0.02 | -7.9 | 88.02 | 0.03 | 105.74 | 0.02 |
| … | | | | | | | |
| 80 | 139.24 | 0.02 | 0.0 | 87.01 | 0.04 | 104.33 | 0.04 |

Table 2. The list of measurements for the organ pipe - Bourdon 8-foot open, b

| x | $\mu_{F0}$ | $\sigma_{F0}$ | $W_{F0}$ | Microphone no. 1 | | Microphone no. 2 | |
|---|---|---|---|---|---|---|---|
| | | | | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ |
| [mm] | [Hz] | | [cent] | [dB] | | | |
| 0 | 238.14 | 0.01 | -103.1 | 109.15 | 0.04 | 106.61 | 0.04 |
| 5 | 246.02 | 0.03 | -46.8 | 111.73 | 0.03 | 109.83 | 0.02 |
| 10 | 249.22 | 0.03 | -24.4 | 112.18 | 0.09 | 109.63 | 0.09 |
| 15 | 250.61 | 0.04 | -14.8 | 112.37 | 0.04 | 110.08 | 0.05 |
| 20 | 251.30 | 0.02 | -10.0 | 112.41 | 0.06 | 110.18 | 0.07 |
| 25 | 251.76 | 0.03 | -6.9 | 112.55 | 0.08 | 110.13 | 0.08 |
| 30 | 251.99 | 0.01 | -5.3 | 112.60 | 0.04 | 110.20 | 0.04 |
| 35 | 252.19 | 0.06 | -3.9 | 112.54 | 0.06 | 109.92 | 0.07 |
| 40 | 252.30 | 0.04 | -3.1 | 112.58 | 0.03 | 109.89 | 0.03 |
| 45 | 252.38 | 0.02 | -2.6 | 112.63 | 0.04 | 109.69 | 0.04 |
| … | | | | | | | |
| 80 | 252.76 | 0.02 | 0.0 | 111.55 | 0.04 | 106.99 | 0.04 |

Table 3. The list of measurements for the organ pipe - Principal 4-foot, e'

| x | $\mu_{F0}$ | $\sigma_{F0}$ | $W_{F0}$ | Microphone no. 1 | | Microphone no. 2 | |
|---|---|---|---|---|---|---|---|
| | | | | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ | $F_0$ Sound level $L_{Zeq}$ | Measurement uncertainty $\sigma_{LZeq}$ |
| [mm] | [Hz] | | [cent] | [dB] | | | |
| 5 | 320.59 | 0.03 | -35.3 | 95.72 | 0.02 | 97.45 | 0.04 |
| 10 | 324.14 | 0.02 | -16.3 | 97.77 | 0.03 | 99.80 | 0.05 |
| 15 | 325.28 | 0.01 | -10.1 | 98.04 | 0.05 | 100.70 | 0.07 |
| 20 | 325.81 | 0.02 | -7.3 | 98.20 | 0.04 | 101.34 | 0.05 |
| 25 | 325.90 | 0.01 | -6.9 | 98.22 | 0.02 | 101.67 | 0.03 |
| 30 | 326.16 | 0.01 | -5.5 | 98.19 | 0.03 | 101.94 | 0.04 |
| 35 | 326.28 | 0.01 | -4.9 | 98.34 | 0.36 | 102.01 | 0.03 |
| 40 | 326.37 | 0.01 | -4.4 | 97.98 | 0.03 | 101.90 | 0.04 |
| 45 | 326.44 | 0.01 | -4.0 | 97.99 | 0.02 | 101.90 | 0.03 |
| 50 | 326.49 | 0.02 | -3.7 | 97.93 | 0.03 | 101.80 | 0.03 |
| 55 | 326.52 | 0.01 | -3.6 | 97.90 | 0.02 | 101.67 | 0.04 |
| … | | | | | | | |
| 80 | 327.19 | 0.04 | 0.0 | 98.32 | 0.02 | 100.92 | 0.03 |

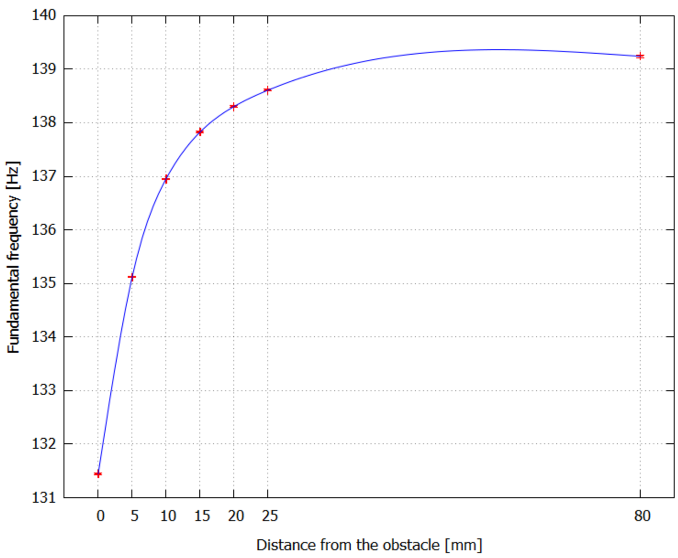


Figure 2. The dependence of the fundamental frequency $F_0$ of the organ pipe on the distance from the obstacle - Bourdon 16-foot stopped, c sharp

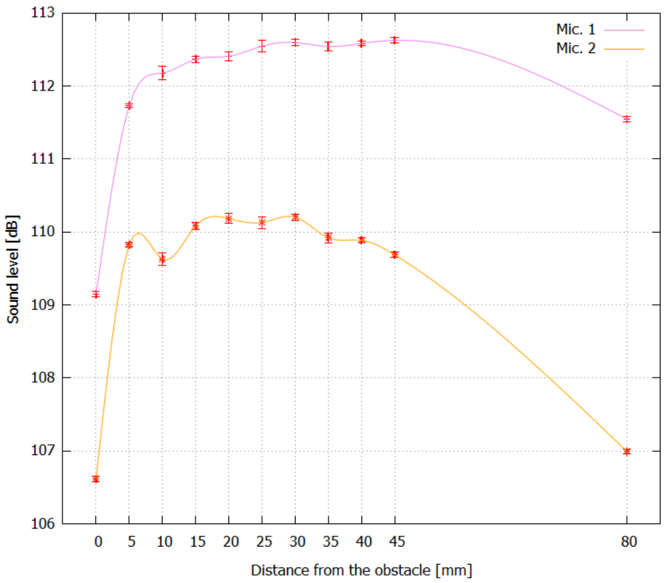


Figure 3. The sound level depending on the distance
from the obstacle - Bourdon 8-foot open, b

The spectra shown in Figure 4 present changes in the harmonics of the pipe sound. All harmonics have a significantly lower sound level at a close distance of the obstacle from the pipe. Odd harmonics (i.e. frequencies $k{\cdot}F_0$, where $k$ = 1, 3, 5, 7…), in the case of an open pipe, have a much lower sound level than without any obstacle. This phenomenon is typical for stopped pipes, but not for the open ones.

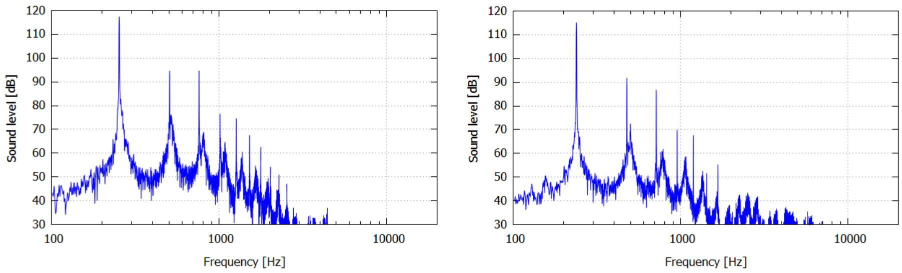


Figure 4. The spectrum of the organ pipe without the obstacle (left) and with
the obstacle at 0 mm distance (right) – Bourdon 8-foot open b, microphone no. 1

## 4. Musical consequences

Based on the measurements, it was found that the presence of an obstacle near the pipe has a significant impact on the pitch of the generated sound. These changes can be as much as circa -100 cents (Figure 5), which in the case of equal temperament means lowering sound pitch by a semitone. An additional consequence of this phenomenon is the time-consuming tuning and intonation of organs, if the pipes are located close to each other. The most considerable change in $F_0$ frequency in terms of the distance was observed for wooden pipes with a rectangular profile.

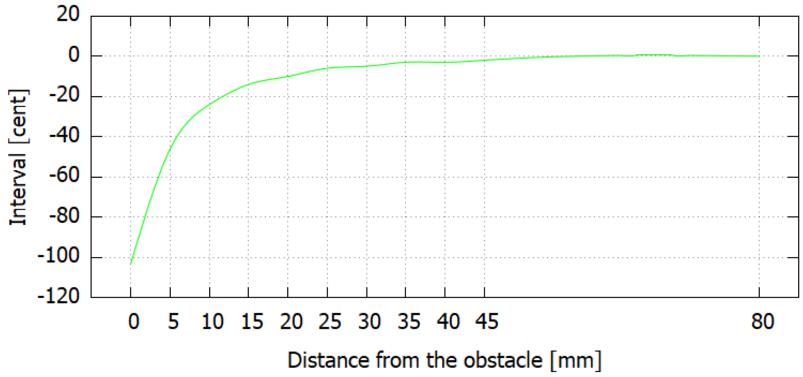


Figure 5. The interval between the tone of the organ pipe without obstacle and with the obstacle - Bourdon 8-foot open h

There was also a change in the sound level depending on the distance observed (Figure 3). For the studied pipes, these changes were about 4 dB. Such a change may also cause intonation problems.

## 5. Conclusions

The results of the presented measurements show an evident effect of the distance between the pipe and the obstacle on the parameters of the generated sound. In the case of pipe organs, such obstacles are other pipes placed on the windchest. These changes are significant for organ building. It can be expected that in the case of the dense arrangement of the pipes, the instrument may not be able to tune.

We found that the impact of the obstacle on sound generation by the organ pipe exists even when the distance between the obstacle and the mouth of the pipe is relatively large. For this reason, knowledge about the behaviour of the organ pipe near the obstacle is very important in the process of designing a windchest.


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