Measurement of sound and flow fields in an organ pipe using a scanning laser Doppler vibrometer

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Abstract  Sound production in organ pipes is a complex matter involving interactions between flow fields and sound waves. Until now, this mechanism has not entirely been understood. In this paper, the complex interaction between the flow and the sound field in the instrument is investigated by using a scanning laser vibrometer. The measurement results are compared with measurements of two more traditional optical techniques (PIV and Schlieren photography) and with microphone sound measurements.

1. Introduction

Even today, the craftsmanship of organ building is mainly characterized by tradition and experience. However, a better understanding of the physics of the sound production would allow organ builders to dimension the pipes in advance, and reach a desired sound character without extensive trial and error. Because of their non-intrusive character, optical measurement techniques are ideally suited for the study of the flow behavior in organ pipes. Since the nineties, several research teams have used the Schlieren technique to visualize the flow field in instruments [1][2]. Because of their qualitative nature, Schlieren measurements are often complemented with LDA [3] or PIV [4] measurements. Although the above mentioned optical measurement techniques have contributed to a better understanding of the flow mechanisms (in the region near the flue and labium), they do not allow the study of the complete flow-sound interaction during the sound production phase (transient and steady state). An attractive alternative technique that is proposed in this article is the scanning laser Doppler vibrometer.

Originally, the LDV instrument was developed for vibration measurements [5], but recently several research teams started to use the technique also for acoustic field [6][7] and flow field [8][9] visualization and to study the aeroacoustic interactions between a flow field and a sound wave [10][11]. Concerning the use of the LDV for blowing instruments, there are some papers reporting the use of the LDV for organ pipe measurements, but the existing work is aimed at the measurement of the vibrations of the instrument walls and the sound waves that are generated at the outlet [12][13]; not focused on the sound generation mechanism. In this paper, we will show that the use of the scanning LDV can be an important aid in the determination of the sound-flow interactions and the sound generation mechanisms of the instrument.

2. Experimental setup

In order to study the flow in organ pipes by means of optical measuring techniques, a transparent copy of a representative, realistic organ pipe was constructed (see Figure 1). A schematic representation of the organ pipe set-up is shown in Figure 2 (see numbers (1) to (5)). The pipe (5) is driven by air delivered by a compressor (1), which is supplied by means of a pneumatic servo valve (4), controlled by a signal generator (2) and powered by a DC power supply of 24 V (3). The amplitude of the applied control signal is determining for the pressure at which the fluid leaves the valve, and the wave form for the rate of pressure rise in the pipe foot, and therefore for the speed of the attack transient. In this paper, the results for a square wave pressure profile are shown (although
also other types of wave profiles were tested).

![Figure 1: Dimensions of the transparent organ pipe.](image)

Figure 2: Schematic representation of the LDV measurement set-up: (1) air compressor, (2) arbitrary wave generator, (3) DC power supply, (4) servo valve, (5) transparent organ pipe, (6) rigid steel block, (7) Polytec PSV400 laser Doppler vibrometer.

### 3. LDV measurement technique

Laser Doppler Vibrometry is an optical measurement technique, based on the Doppler effect. The instrument was developed for measuring the velocity of vibrating objects. Therefore, a laser beam with wavelength $\lambda$ is aimed at a target location and the Doppler shift $\Delta f$ between the transmitted frequency and the frequency of the reflected beam is measured. The total frequency shift can be written as:

$$\Delta f = \frac{2}{\lambda} \left( v \cos \beta + \frac{\partial n}{\partial p} \int_{\text{vibrometer}} \frac{d(\Delta p(x,y,z,t))}{dx} dl \right)$$

Hereby, the first term equals the Doppler shift caused by the relative displacement of an object, oriented with an angle $\beta$ and moving with a velocity $v$ with respect to the laser beam, while the second term accounts for the fluctuations in optical path length, caused by the fluctuations in the
refractive index $n$ originating from pressure fluctuations $\Delta p(x, y, z, t)$ in the surrounding medium.

When, as in general, the LDV technique is used to measure the velocity of a vibrating object, the contribution of the second term is usually negligible. But, when the laser beam is pointed to a rigid reflector, instead of to a vibrating object, the first contribution is negligible and the influence of the fluctuations in refractive index, however small, can be detected. This technique, developed by Zipser and Franke is called Refracto-Vibrometry and can be used for the measuring and visualizing of acoustic waves in gases and liquids [14]. Figure 2 shows the schematic representation of the set-up used for the LDV measurements. The organ pipe (5) was placed between a rigid reflector (6) and a Laser Doppler Vibrometer (7). It was driven by compressed air (1), which was supplied to the pipe by means of a servo valve (4), as was described in Paragraph 2.

4. Measurement results

4.1 Measurement technique

To investigate the benefits of the use of the LDV technique for this application, the measurement results are compared with results of two more traditional optical techniques, namely PIV and Schlieren photography. The Schlieren technique is an optical measurement technique, based on differences in index of refraction. In order to provide these refractive differences, the organ pipe was driven by CO2 instead of air for these measurements. This influences the acoustic characteristics, but does not change the conclusions on the flow [3]. A Z-type 2 mirror system [15] was used.

For visualizations with the PIV technique, the air flow was seeded using a Topas aerosol generator (DEHS). The particles are inserted in the flow before the inlet of the organ pipe. For both the Schlieren and PIV measurements, a Nd:YLF laser (Quantronix Darwin DUO-527-80-M) was used for the illumination, and the images were captured by a high speed camera (Photron FASTCAM-SA1.1).

4.2 Results

When opening the valve, the attack transient is set in. Air will flow into the pipe foot and emerge from the flue exit, travelling towards the labium. After the contact with the labium, oscillations will start to grow. As soon as a (quasi) steady oscillation with a frequency, equal to the fundamental frequency of the standing wave formed in the resonator, is reached, the attack transient passes into a so-called quasi steady state. Figure 3 shows three time instants of the transient state, measured by the PIV, Schlieren, and LDV technique. The figures show the flow in the mouth of the pipe, i.e. the region around the flue exit and the labium. Since each technique is based on the measurement of a different quantity, different aspects of the flow can be detected in the measurement results. The PIV technique tracks the displacement of seeding particles that follow the movement of the flow. The measurement results (Figure 3 (a)) clearly show the emerging of the jet from the flue, and the formation of a pair of vortices. Behind this head vortex, an alternating series of vortices is introduced. Because of the significant mass flow during the blowing process the seeding particle concentration rapidly decreases. Moreover, after the jet hits the labium the flow becomes more turbulent and no useful information can be obtained any more from the 2D PIV measurements. Therefore, for visualization, the PIV technique has shown to be only useful for the initial development of the flow.

The Schlieren technique visualizes the flow by using spatial refraction index inhomogenities that result in diffraction of light on a screen. Since the Schlieren technique is sensitive to variations in
refractive index, it is the derivative of the density field that is imaged. In this technique the result includes an integration of the density field over the optical path of the laser, in contrast to the PIV technique, where only a planar sheet is illuminated and recorded. Also, the sensitivity of the Schlieren technique is lower than for PIV as can clearly be seen from the contrast in Figure 3b.

![Figure 3a](image1.png) ![Figure 3b](image2.png) ![Figure 3c](image3.png)

Figure 3: Visualization of the transient behavior using the (a) PIV, (b) Schlieren, (c) LDV technique

The LDV technique is based on the measurement of pressure differences (see Equation 3) and shows the distribution of the pressure. At time instant $t_3$, Figure 3 (c) clearly shows how the vortex impinges on the labium is split up in an over- and under-pressure on the upper and lower part of the labium. With PIV and Schlieren measurements it was not possible to clearly observe this phenomenon (although a qualitative agreement between Figure 3(b) and (c) at $t_3$ can be observed).

![Figure 4a](image4.png) ![Figure 4b](image5.png)

Figure 4: Schlieren and LDV measurements at four, equally spaced time instants of one fundamental period of the steady state.

The attack transient is followed by a steady state, which is characterized by a steady oscillation of the air jet around the labium. The oscillation frequency equals the fundamental frequency of the standing wave formed in the resonator, and is thus imposed by the length of the resonator. Figure 4(a) shows the Schlieren flow visualization at four, equally spaced time instants of one fundamental period of the steady state, while Figure 4(b) shows the corresponding LDV measurements. It can be observed that, for the Schlieren measurements, the global oscillation of the jet around the labium
can be clearly distinguished. The LDV measurements, on the other hand, show a global alternation of compression and rarefaction; the pressure introduced by the pressure waves in the resonator are larger and mask the pressure differences introduced by the oscillating jet. The jet oscillation can be extracted by substracting the mean value LDV images from the measurements. The LDV technique thus offers the possibily of visualising acoustic phenomena, while the Schlieren technique is restricted to the flow. Since the LDV technique also allows flow visualization in the resonator, it is possible to link the flow development in the pipe mouth to the behavior in the resonator.

So LDV measurements can give detailed information about the acoustic phenomena occuring in the attack transient, about the start of the propagation of the pressure waves in the resonator, and the exact launch of the steady state. LDV measurements can therefore be very useful in the study of sound generation in flue instruments.

Furthermore, since for the LDV technique, measurements are performed in a specified time range, the result is a set of data as a function of time, which can be subjected to a Fast Fourier Transform to obtain the acoustic waves. Figure 6 (a) shows the LDV measurements of the acoustical mode shape at the first harmonic (306 Hz), while (b) shows the result of a flow simulation in Comsol at the first acoustic mode (314 Hz). Keeping in mind that the boundary conditions for this problem are complex and unknown, the simulation gives a good agreement with the measurements. However, it should be noted that to obtain this good result, in the simulation, the height of the pipe was slightly adapted.

Figure 4: Visualization of the steady state behavior using the (a) Schlieren, (b) LDV technique

A major strength of the LDV technique is the fact that it also allows flow visualization in the resonator over a length of about 45cm. This is very interesting, since the flow development in the pipe mouth can in that way be linked to the behavior in the resonator. Figure 5 shows the visualization of the flow at four time instants of one pressure cycle in both the pipe mouth and the resonator. The figure shows that not only the oscillating flow but also the propagating acoustic wave are visible.

Furthermore, the time data of the LDV measurements can be subjected to a Fast Fourier Transform, in order to obtain the standing waves. The top of Figure 6 shows the LDV measurements of the steady state sound wave in the pipe at the first harmonic (306 Hz). In Figure 6 the measurement result is compared with an acoustic simulation in Comsol Multiphysics (only the first acoustic mode at 314 Hz is shown). It has to be taken into account that in the simulation the open-closed boundary
condition were chosen while this does not agree with the real boundary conditions of the pipe. Keeping this limitation in mind the agreement between simulation and experiment is quite good.

Figure 5: Visualization of the pipe mouth and resonator (steady state results at four phases)

Figure 6: Comparison of the measured standing wave and the FEM simulation in COMSOL.
5. Conclusions

The LDV is a useful aid in the research of flow generated sound fields in musical instruments like the organ pipe. The LDV measurement shows the pressure distribution in the measuring zone and therefore highlights other flow aspects than the traditionally used PIV or Schlieren technique. Because the flow field as well as the sound field can be measured in the complete instrument, the flow development in the mouthpiece and resonator can be studied together.

References