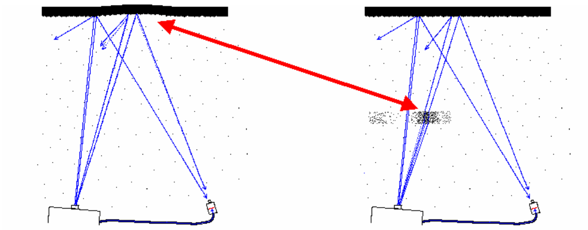

Figure 7: Due to light beams phase changes, the non moving surface in the background, illuminated through an environment with diverse features, seems on the camera speckle pictures as if it is displaced.

The air in normal conditions has its refraction index very low: $\boldsymbol{n}_{air_{normal}}$ = 1.0002718029 (λ = 632.8 nm/ p_{normal}). If the sound pressure level is 100 dB, the air pressure alters from the normal value $p(t, xyz_X)$ = 101325 Pa to values between peak values (normal + acoustic) $p(t, xyz_X)$ = -101323 and +101327 Pa. Then the refraction index varies up to the peak value (substituted in the relation *2*; taken only + value):

$$n_{air_{\text{normal+acoustic}}} = 1 + 7{,}8607.10^{-7}.\frac{101327}{293} = 1{,}0002718434 \quad ,$$

and shift of phase ($\Delta\theta$ in the relation *6* after substitution) is:

$$\Delta\theta \cong \frac{360.3.10^{5}}{6{,}328.10^{-7}}.\frac{0{,}1(1{,}000271802\,9 - 1{,}000271843)}{3.10^{5}} = +2{,}3^{\circ}.$$

Even thought the sound pressure level of 100dB is great in a usual acoustic environment, it is still not sufficient for ESPI visualization. Such a small phase shift ($1/78\pi$) is not recognizable with this technique. Generally, a good differentiation of very small phase shifts with double pulse TV holography method is influenced: 1) by the adjustment of laser illumination and 2) by relative displacement of a surface in the background. For this type of sound pressure visualization the self vibrations of both the background surface and also the ESPI laser head (and camera) are not negligible, because we must use a long interval between the first reference pulse (which illuminates the background through air in its standing stage) and second recording pulse (which illuminates the background in synchrony with a temporal course of an observed air feature, here in synchrony with course of sound pressure). These self vibrations are excited mainly by the motion of the building (can be evoked also through an acoustic way). Even if these vibrations are minimized, they always bring a measurement noise (usually comparable with phase shifts up to $1/10\ \pi$).

The simplest solution to this sensitivity problem is to increase the refraction index (and thus its changes) in the inserted environment or to have a substantially greater distance *l*. Since CO_2 has its refraction index relatively sufficient ($\boldsymbol{n}_{CO_2\ normal}$ = 1,0004174/ 20^{o}C, p_{normal}) and air contains it, it is possible to increase air refraction index through mixing this gas with normal air (the increase of CO_2 concentration). The CO_2 concentration would be chosen in correlation to distance *l* of an inserted environment and to the peak values of sound pressure. A suitable shift of phase θ would be approximately π and more. In the case of wind musical instruments, when their sound is excited naturally by an air flow, the mixing of CO_2 with air can be done similarly as in a cars carburetor.

3. MEASUREMENT EXAMPLE

Figure 8 presents an example of a use of a mixture of 80% volume unit of normal air with 20% volume unit of pure CO_2 (20^{o}C, p_{normal}) for visualization of sound pressure inside and outside of an organ pipe in the process of normal excitation (both side walls of this pipe were from glass).

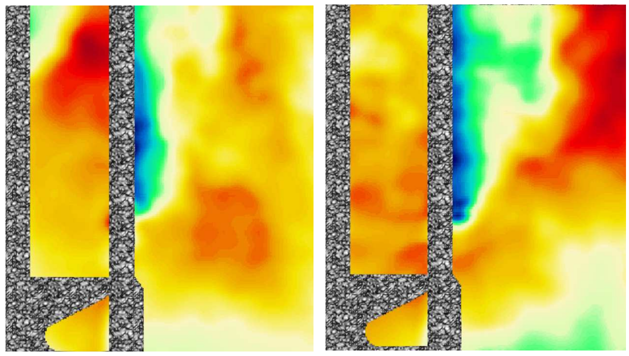

Figure 8: Distributions of sound pressure inside and outside of an organ pipe in the process of normal excitation.

The images (Figure 8) show two different sound excitation stages that are captured in synchrony with the sound pressure recorded by a microphone. Red (and yellow, see scale in Figure 9) colors in images visualize areas in these environments with positive laser light phase shift. This is caused by the positive values of sound pressure in those areas, which cause lower values of velocities of laser beams passing this way and therefore higher values of refraction index in comparison to normal air. The blue (and green) colors visualize opposite values (the relations *p*, *n*, *v* and theirs mapping to a color are: $\boldsymbol{p}_{air_{normal+SP}} - \boldsymbol{p}_{air_{normal}} \rightarrow \boldsymbol{n}_{environm.} - \boldsymbol{n}_{air} \rightarrow \boldsymbol{v}_{air} - \boldsymbol{v}_{environm.} > 0 \rightarrow$ ●● $\boldsymbol{p}_{air_{normal+SP}} - \boldsymbol{p}_{air_{normal}} \rightarrow \boldsymbol{n}_{environm.} - \boldsymbol{n}_{air} \rightarrow \boldsymbol{v}_{air} - \boldsymbol{v}_{environm.} < 0 \rightarrow$ ●●).

Such relations between ESPI images color scale and positive or negative difference of environment features can be well demonstrated in an image example (Figure 9), in which a CO_2 environment or only a hot air environment is used (Figure 9 Left: CO_2 decreases lights velocity; Right: hot air increases lights velocity; both environments were produced as a jet in air).

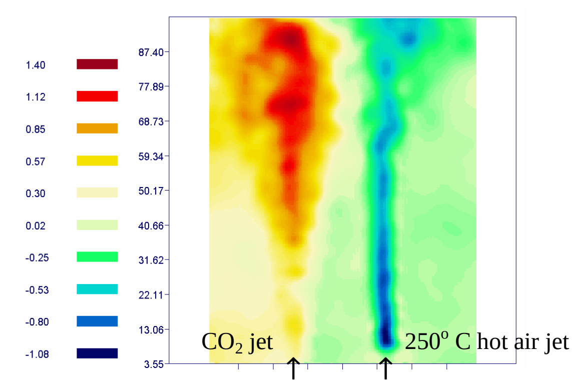

Figure 9: Positive phase shift of laser light in a CO_2 jet (red and yellow colors) and negative phase shift in a hot air jet (blue and green). Both jets go from its sources ↑ bottom-up.

4. CONCLUSIONS

The presented method of sound pressure visualization appears to be an applicable way to study such problems, where other methods are often complicated or do not exist. In this paper the practical outputs are focused on applications on wind musical instruments, especially on organ pipes, but this can be extended on other spheres of interest, based on air density, pressure or temperature changes. Of course, even if the use of this method is simple, in cases where the studied gaseous environments are inside boxes, a complication can arise, because these boxes must be constructed to be transparent for laser light.