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Experimental study of the fluid-structure-acoustic interaction in a human voice model

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For the investigation of the physical processes of the human phonation a fluid-structure-coupled in-vitro model was developed, which constitutes a copy of the human larynx. With that model one was able to reproduce a manlike process of sound production.

The model made it possible to enforce extensive observations of the flow-induced vocal fold vibrations. Many measurement techniques were applied as high-speed flow visualization, particle image velocimetry (PIV) of the time-dependent flow field, unsteady pressure measurement, vibration measurement by a laser-scanning vibrometer as well as the measurement of the acoustic field. Furthermore correlations were done between the acoustic field, the flow velocity and the displacement of the vocal fold models.

The results support the existence of the Coanda-effect during phonation. The flow attaches to one vocal fold just past the glottis and forms a spacious vortex behind the vocal folds. That behavior is not linked to one vocal fold and changes stochastically from cycle to cycle. The sound production is presumed to be produced by oscillations of the vocal folds and therefore by the involved oscillating volume flow rate.

1 Introduction

Human voice production arises from oscillations of the two opposing vocal folds (VFs) within the larynx. The gap between the VFs is called glottis. Increased subglottal pressure causes an airstream through the glottis and excites vocal fold (VF) oscillations (fig. 1). Due to the periodic opening and closing of the glottis the airstream is modulated, which generates the basic tone of the human voice. Subsequently, this tone is filtered by the vocal tract and emitted as acoustic signal through the mouth [1].

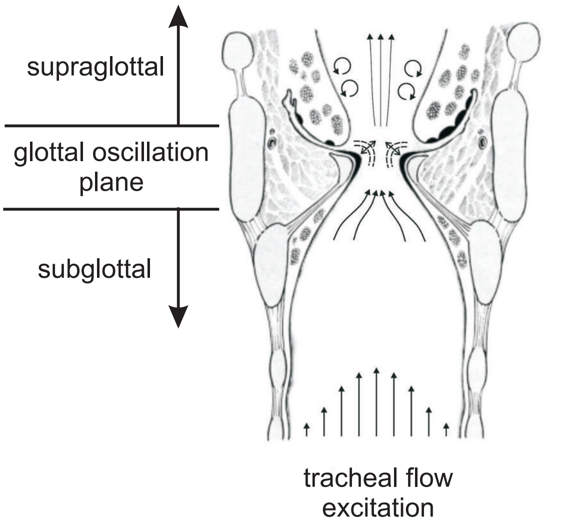


Figure 1: Schematically sketch of the vocal tract

The objective of these investigations is to understand the physical mechanism of the human phonation in detail.

Previous works can be divided into investigations on rigid configurations of VFs with a constant and modulated volume flow rate, respectively, and into experiments with oscillating VFs. The advantage of rigid VFs [2, 3, 4] consists in a better accessibility for optical measurement techniques as well as for pressure sensors inserted in the walls of the synthetic glottal duct. Because of the very good repeatability single phenomena in the flow field could be investigated very well. The main focus lies on the *Coanda* effect [2, 5], (attachment of the flow to one VF and separation from the other), the fluctuating separation-lines on the VF [6, 7] and the sound production by the turbulent flow field [8].

The second approach considers the periodical movement of the VFs. Thereby one has to distinguish between externally driven and flow-induced oscillating synthetic VFs. Externally impressed VF vibrations were used in [7, 9]. Triep et al. [10] went a similar way. They did phase-resolved investigations of the flow field applying digital particle image velocimetry (DPIV) during the whole cycle. However driven models don't preserve the energy balance between fluid and structure because energy is brought in the flow by the driving unit.

To model the fluid-structure-acoustic interaction process of human phonation and therefore to restrain the energy balance, synthetic VFs had to be produced, which show flow-induced oscillations at typical flow rates during human phonation. Thomson et. al [11, 12] and Neubauer et al. [13] used self-oscillating models of the VFs consisting of a polyurethane rubber with the characteristic stiffness of human VFs. They investigated the flow field in the supraglottal region to determine the aerodynamic energy transfer to the VFs and to identify coherent flow structures within the flow.

The time-dependent cross-section of the glottal duct during phonation is displayed in fig. 2. It is based on the model of Hirona et al. [14]. The glottal duct changes its form from convergent during the opening to divergent during the closing of the glottis. However it has not been possible yet to measure the cross-section of the glottal duct directly within a human patient with high accuracy during phonation.

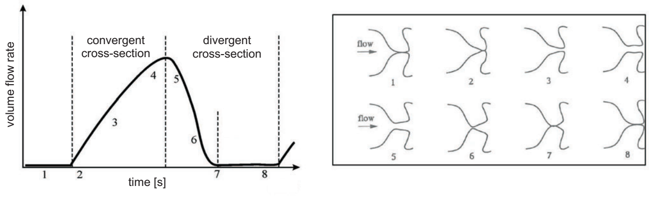


Figure 2: One cycle of the movement of the glottis (see [14])

In the present work the full fluid-structure-acoustic interaction of the human phonation process is reproduced. Therefore synthetic VFs were used, which show oscillatory behaviour within a fluid-structure interaction. Furthermore a clear acoustic signal was emitted and could be detected in the far field. This acoustic tone assures the right transformation of the natural human process into the simplified experimental setup and it becomes possible to analyze the physical processes of the sound generation.

The experimental model of the human larynx permits detailed observations of the characteristic flow parameters with the aim to identify the acoustic sources of the human voice. Three mechanisms of sound production have to be considered:

- Flow-induced structure vibration of the VFs
- The pulsating mass flow due to the periodical opening and closing of the glottis
- Turbulent structures in the flow behind the VFs

Because of the very high damping properties of the mucous membrane, which covers the VFs, the structural sound is neglected. Hence the influence of the remaining mechanisms on the human phonation were investigated.

2 Experimental setup

During the experiments synthetic VFs were used whose geometry relates to the shape of human VFs [15] with a 1:1 length scale (see fig. 3). They were made by casting a liquid polymer solution into a mold. The solution consists of a two-part polyurethane composition mixed with a liquid softener: cure polymer Evergreen$^{\mathrm{TM}}$ 10 and Everflex$^{\mathrm{TM}}$ for increased flexibility. Adjusting the mixing ratio of the three parts results to synthetic VFs with a Young's modulus of $E = 6.5\,\mathrm{kPa}$, which is in the range of Young's moduli found in human tissue. To reproduce the inhomogeneous material distribution in human VFs a rigid mass layer was inserted in each tip of the VFs. This resulted in increased oscillation amplitudes of the synthetic VFs and consequently improved the acoustic signal.

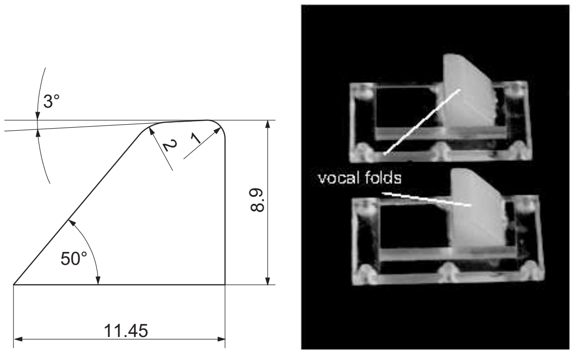


Figure 3: Vocal folds design, all dimensions in [mm]

The geometric dimensions of the test channel were adapted to the human larynx. Figure 4 shows a schematic diagram of the test rig. It consists of an unsteady mass flow controller, which delivers constant flow rates in the range of 9 to 30 $\frac{\mathrm{l}}{\mathrm{min}}$, which are characteristic for human phonation, for the current investigations. It is followed by a settling chamber, which leads the flow over a nozzle into the main test channel. The channel with rectangular cross-section of $15\,\mathrm{mm} \times 17.8\,\mathrm{mm}$ consists of Plexiglas and contains the synthetic VFs. In contrary to other works with flexible synthetic VFs ([11, 13]) the glottis enters in a channel with the same cross-section as the subglottal area, which models partly an artificial simplified vocal tract.

The flow field in the supraglottal region was investigated with phase-resolved particle image velocimetry (PIV). Therefore the recording time was triggered by the unsteady pressure upstream of the glottis.

Moreover to analyse the fluid-structure-acoustic interaction the unsteady pressure upstream and downstream of the artificial glottis and the unsteady flow velocity obtained by constant temperature anemometry (CTA) using a hot wire was correlated with the acoustic pressure in the far field. Furthermore the structure velocity of the VFs was determined by a laser scanning vibrometer (LDV). The displacement of the synthetic glottis was visualized using a digital high-speed camera which was triggered analogically to the PIV measurements.

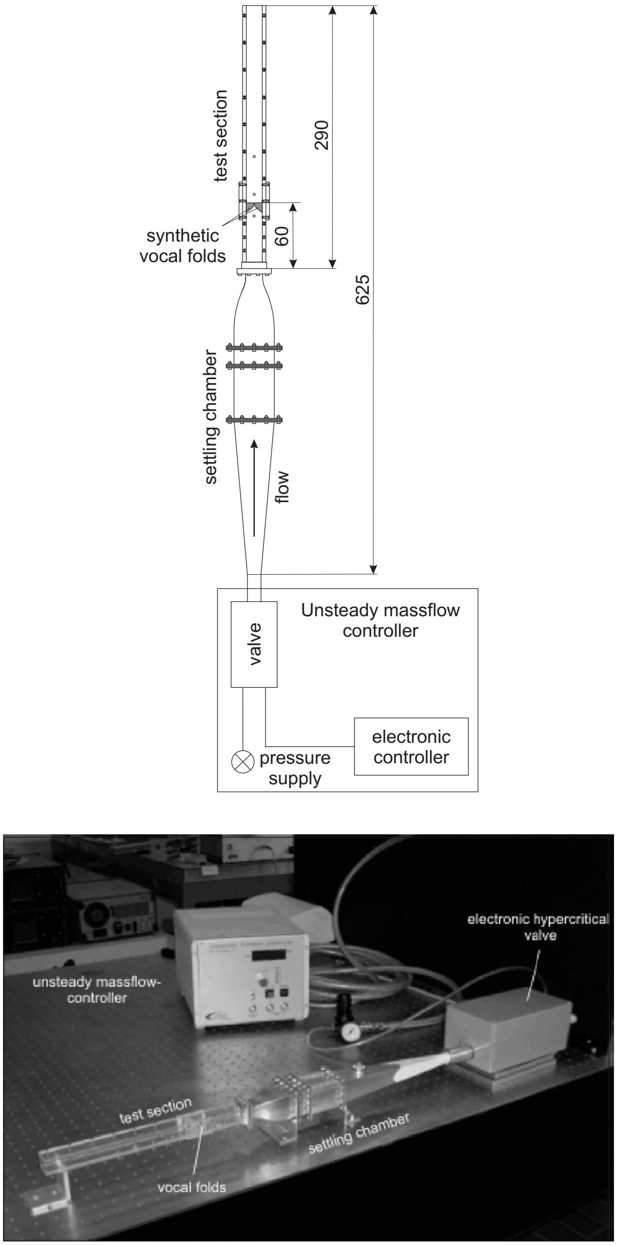
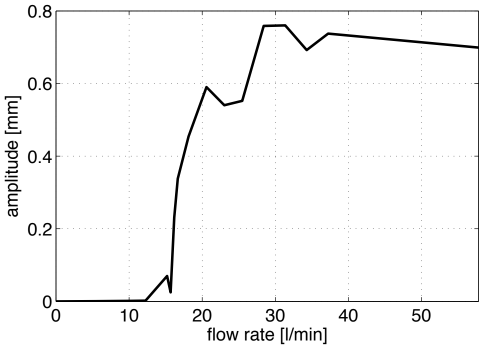


Figure 4: Schematic diagram and a photo of the basic test rig, all dimensions in [mm]

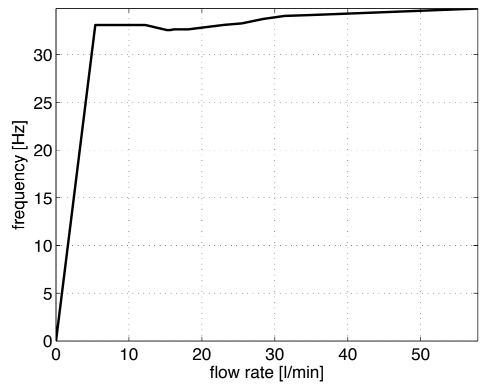
3 Results

In the following the results of the measurements for the oscillating synthetic VFs are presented using a flow rate of $\dot{V} = 23.03 \,\frac{\mathrm{l}}{\mathrm{min}}$.

The synthetic VFs vibrated at a frequency of about 34 Hz at their resonance frequency. Increasing the flow rate increases the amplitude of the oscillation (fig. 5(b)) but doesn't affect the frequency significantly (fig. 5(a)). The oscillation produced a clear tonal sound and a broadband noise.



(a) Oscillation amplitude depending on flow rate



(b) Oscillation frequency depending on flow rate

Figure 5: Oscillation frequency and amplitude of the synthetic VFs depending on the flow rate

The form of the synthetic glottis is in a very good consistency to a human glottis during phonation as could be seen in fig. 6.

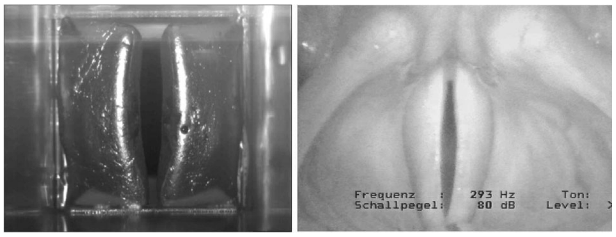


Figure 6: Glottis of the test model and of a human patient during phonation

In fig. 7 the VFs are plotted depending on the pressure distribution upstream to the glottis. Thereby a whole oscillation cycle is shown. The single pictures were made by a digital high-speed camera.

The pressure distribution is characterized by a nearly perfect sinusoidal behaviour. The glottis width shows a periodical opening and closing. It occurs a phase shift of approximately $\Delta\alpha = 5/12\,\pi$ between the complete closure at $\alpha = 0$ and the maximum pressure at $\alpha = 5/12\,\pi$. This phase shift originates from the complex interaction of the different inertia of the fluid and the VFs, the elasticity and the fluid forces within a fluid-structure-interaction process.

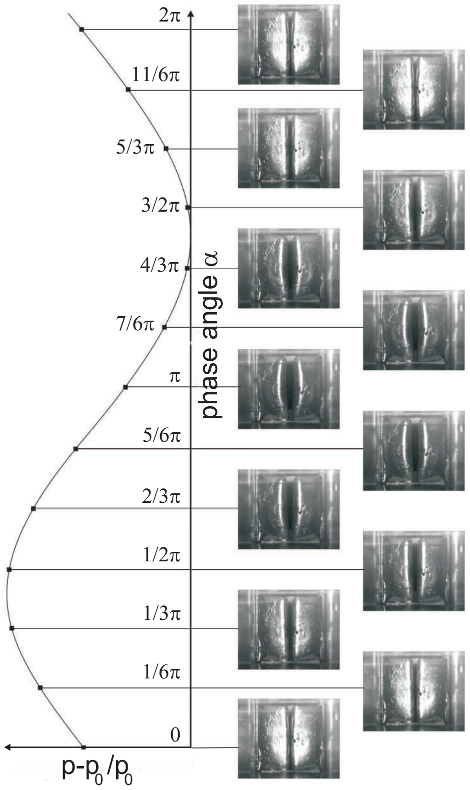


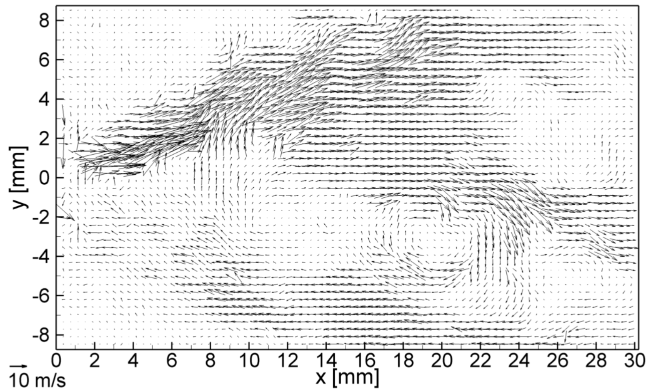
Figure 7: Periodical opening and closing of the synthetic glottis during one cycle depending on the pressure upstream of the artificial glottis

Regarding the plane perpendicular to the glottis the two-dimensional flow field contains a jet, which arises from the narrowest gap in the glottal duct and separates from one fold further downstream. Simultaneously it attaches to the other fold, that is the flow field is strongly asymmetric (see fig. 8(a)). This effect is called *Coanda* effect and is firstly described by Coanda [16]. Moreover the jet is not attached to the same VF in different cycles, but changes the attached fold stochastically. This is called bifurcation of the flow and means, that there are two stable modes of the flow field, which can be assumed (see fig. 8).

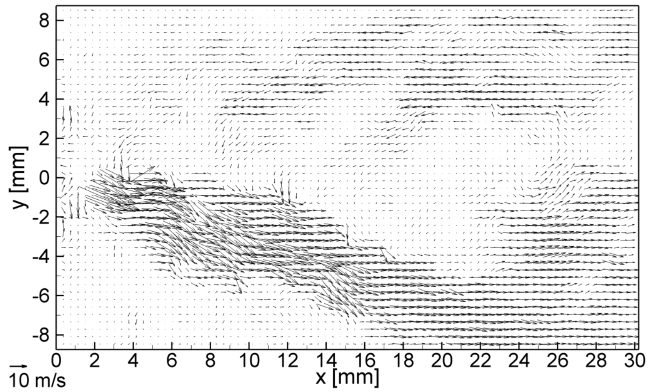
Figure 9 shows the phase-averaged flow field for four different phase angles within a cycle. For each 300 single vector plots of one phase angle were averaged, on which the jet is attached to the upper VF.

The the jet stayed attached to the same VF during one cycle. The angle between the jet axis and the centerline of the channel decreases from the phase angle $\alpha = \frac{1}{2}\pi$ to $\alpha = \frac{5}{3}\pi$. Thus the large recirulation area below the jet is displaced in downstream direction.

As mentioned above, during the measurements a clear tonal sound and a broadband sound could be heard in the acoustic far field. The tonal component is generated by the pulsating flow rate due to the periodical opening and closing of the glottis. To identify the phys-

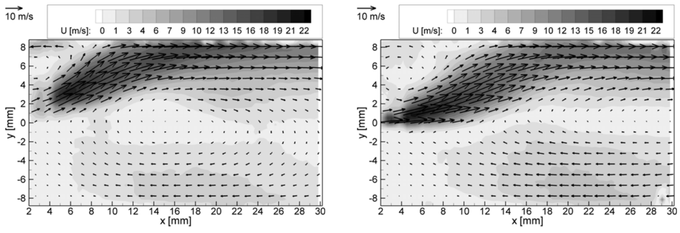


(a) Jet attached to the upper VF

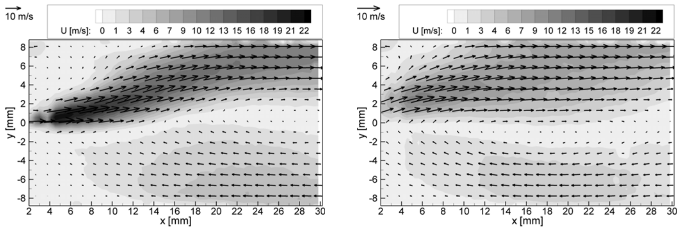


(b) Jet attached to the lower VF

Figure 8: Velocity vector plots at the same phase angle in different oscillation cycles obtained by PIV



(a) Phase angle $\alpha = \frac{1}{2}\pi$ (b) Phase angle $\alpha = \frac{5}{6}\pi$



(c) Phase angle $\alpha = \pi$ (d) Phase angle $\alpha = \frac{5}{3}\pi$

Figure 9: Phase-averaged flow velocity behind the oscillating VFs models of the first three instants of a oscillation cycle

ical mechanisms of the broadband sound production, simultaneous measurements of the wall pressure upstream and downstream to the glottis (UWPU and UWPD), the acoustic pressure in the far field (AP) and the unsteady flow velocity downstream to the glottis were performed (CTA). All these signals were correlated with the acousitc pressure (AP) to give information about the acoustic sources. Figure 10 displays the amplitude spectra of the measured signals and additionally the spectrum of the structural velocity in flow direction obtained by LDV.

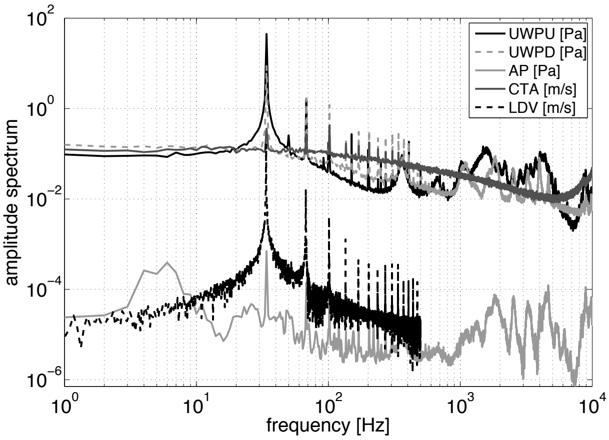


Figure 10: Amplitude spectrum of the unsteady wall pressure upstream (UWPU) and downstream (UWPD) to the glottis, of the unsteady flow velocity downstream to the glottis (CTA), of the acoustic pressure in the fare field (AP) and the structural velocity of the VFs (LDV)

The acoustic spectrum (AP) shows a maximum at a frequency lower than 10 Hz, which is related to environmental noise. The major peak occurs at $f = 34\,\mathrm{Hz}$, which constitutes the tonal sound and is directly related to the oscillation frequency of the VFs as can be seen in the spectrum of the structural velocity (LDV). All other spectra possess their major peaks at the same frequency except the unsteady flow velocity (CTA). Here the maximum is located at the frequency of the third harmonic at approximately $f = 102\,\mathrm{Hz}$. This is due to the position of the sensor for the hot wire measurements, which is located in the center point of the channel. It detects the passing of the large vortex below the jet and the jet itself (the jet axis lies almost on the centerline at the end of a cycle, see fig. 9(d)). The higher harmonics of the wall pressures (UWPU and UWPD) and the acoustic pressure (AP) are assumed to be the result of resonant processes in the channel.

Furthermore the spectrum of the acoustic pressure (AP) shows a broadband noise for $f > 1000\,\mathrm{Hz}$. This is also observable in the spectra of the wall pressures (UWPU and UWPD). However this behaviour cannot be seen in the spectrum of the flow velocity (CTA). On this account the instabilities generated in the shear layers of the jet give no dominant contribution to the production of the broadband noise. Moreover considering a Mach-number lower than 0.1, the maximum jet velocity within a cycle of $22.5\,\frac{\mathrm{m}}{\mathrm{s}}$ is too low to create a determinative acoustic source term in the shear layers (see [17, 18]). However taking into account the asymmetric flow field downstream of the synthetic glottis (see fig. 9), there is an oscillating pressure distribution on the downstream facing surfaces of the VFs. It is caused by the pulsating jet, which interacts with the backsides of the VFs. This generates a sound very similar to trailing edge noise with a broadband character [19, 20].

4 Conclusion

Extensive investigations were made by using a model of the human larynx. It contains flexible synthetic VFs, which show flow-induced oscillations analogically to human VFs. Beside a broadband sound, a clear tonal sound was produced and detected in the far field. In comparison to other works, the test rig includes a part of the vocal tract in a simplified form, which results in small oscillation amplitudes of the VFs due to the lower pressure difference over the glottal duct. Therefore, a rigid mass layer was inserted in each tip of the VFs, which constitutes the inhomogeneous material distribution of human VFs.

Detailed observations of the supraglottal flow field showed the *Coanda* effect as well as the bifurcational behaviour of the flow. The jet separates from one VF and attaches to the other. This effect is not linked to one VF. The jet changes the VF stochastically from cycle to cycle, but stays attached to the same fold in one cycle.

The synchronous measurements of the unsteady wall pressures, the acoustic pressure and the unsteady flow velocity identified the pulsating flow rate as main acoustic source for the tonal sound. Furthermore the amplitude spectra showed that the instabilities in the shear layers of the jet play a minor role in the production of the broadband noise. The asymmetric flow field suggests that the broadband sound is generated by the asymmetric pressure distribution along the backsides of the VFs. This is the result of the interaction between the jet and the synthetic VFs, which constitutes a similar mechanism to trailing edge noise. How far this assumption applys, further detailed investigations have to prove. Additionally, we will take the tension within the VFs into acount.

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