

# Haptical Exploration of an Unsteady Flow

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## ABSTRACT

This paper investigates a human-centered approach for the exploration of large data sets resulting from CFD (Computational Fluid Dynamics) simulations. In a VR (Virtual Reality) immersive environment we propose to couple haptic feedbacks with visual rendering. The proposed solution aims at identifying critical points of an unsteady fluid flow without resorting to any topology analysis such as eigen analysis of the vector field Jacobian. In a first step, while exploring the data volume, a vibration alerts the user on the presence of critical points in the local volume surrounding the probe position. In a second step, critical point properties are emphasized by means of a visuo-haptic feedback. A set of experiments confirms the effectiveness of the proposed approach. Thanks to the combination of haptic feedbacks with the visual materialization of critical points and streamlines, users were able to easily localize, analyze and focus on specific critical points, selected by experts as representative of the flow topology.

**KEYWORDS:** Data Visualization, Flow Exploration, Haptic Feedback, Virtual Reality

**INDEX TERMS:** [User Interfaces]: Haptic I/O; I.3.7 [Computer Graphics]: Virtual Reality; I.3.6 [Computer Graphics]: Interaction Techniques

## 1 INTRODUCTION

By resolving equations governing the dynamics of fluid flow, CFD (Computational Fluid Dynamics) aims at simulating complex phenomena. The result of such simulation is represented by a (very large) data set defining characteristics of all the fluid particles at any instant of the simulation. However, because of their multidimensional aspects, the understanding of such results is often difficult and time consuming [20]. In addition to automatic exploration processes (direct flow visualisation, feature-based flow visualization [7]) where only the visual feedback is exploited, human-centered approaches can be addressed to tackle the analysis of these results. By taking advantage of all sensory-motor capabilities of humans (visual, haptic and auditory) our goal is to provide a better comprehension of the studied phenomenon. Moreover, by involving the CFD scientist into the exploration process, elements such as past experiences or a domain proficiencies may also contribute to improve the end-user analysis [18].

VR (Virtual Reality) technologies, thanks to an intuitive and multimodal (visual, haptic and audio 3D) interaction provide an adequate environment to fully take advantage of all the user perception capabilities in the exploration process. In particular, regarding the analysis of large data sets a visual/haptic feedback

can be very useful to enhance the level of understanding of scalar and vector fields [19]. In some cases, the haptic rendering gives access to parts occluded or hard to render by a visual feedback alone [2]. In the other hand, because of its great potential in the rendering of local properties, haptic perceptions reinforce visual details [17]. Furthermore, haptic rendering alleviates an overloaded visual channel in pure visual applications.

This paper presents a real time haptical flow exploration method. The approach works as follows: identify the location of all the critical points within the flow field and analyse the type of each critical point. After a brief review of related works in section II, section III recalls some preliminaries related to critical points. Section IV details our approach. Section V describes the evaluation of this method. Section VI concludes the paper.

## 2 RELATED WORK

During last two decades, various scientific and industrial applications have promoted haptic techniques in the exploration of large data sets. This integration has lead to some skillful results. Through this section we briefly summarize some of them. We divide these works into two categories: abstract and CFD data rendering. In the first subsection we discuss mainly about scalar and vector fields, while the second one reviews data sets resulting from CFD simulations.

### 2.1 Haptic Rendering of Abstract Data

The haptic feedback has been in a lot of cases a powerful tool for the understanding of some meaningful properties of scalar and vector fields.

A classical technique is the mapping of the field value onto a viscosity [10] [20]. While moving in the data volume the user is provided a viscosity feedback proportional to the field value at the probe position. Hence, regions having high values feel more viscous to the user. Later evaluations of Van Reimersdahl et al. [23] reveal that this metaphor can be very useful for rapidly scanning a volume in order to identify interesting regions.

In [20] a set of haptic methods is proposed by Pao et al. in order to provide a complementary information channel for conveying certain data properties. For example, the "Pseudo-Gravity" method attracts the hand of the user in regions having high density, while the "Gradient viscosity" offers a frictionless movement in isosurface exploration. For vector field data, one notes the "Orientation Constraint" which informs on the orientation of the field by limiting the hand of the user according to the direction of the vector field.

With techniques such as the intermediate representation [1] [15] and the direct rendering [2] [16] of isosurfaces, the haptic feedback makes it possible to simulate the response of touching a virtual surface. Haptics provide much more information related to local properties, hence the gesture of the user is more accurate in the exploration task. In the medical imaging domain, haptic-assisted segmentation facilitates and speeds up user interactions [3] [22]. In [25] Vidholm et al. relate that in surface segmentation, users work more efficiently when they are guided by a haptic feedback than without such guidance.

More recently the haptic feedback has allowed simulating local properties of a volumetric data through a set of haptic

primitives [12]. A viscosity mode is implemented by using a point primitive, while a line primitive lets the conveying of the orientation of a vector field. Finally, a surface and a friction mode represent implicit and penetrable surfaces respectively.

## 2.2 Haptic Rendering of CFD Data

Several works have contributed to a better understanding of large data sets resulting from CFD simulations. Let us briefly review some of them.

In [6] Durbeck et al couple a haptic interface with a visual feedback in scientific visualization tool, allowing the simultaneous possibility to see and feel a vector field. In the proposed system, the haptic display presents each vector as a force corresponding to the magnitude and the direction of this vector while the graphic one presents a subset of the vector field as streamlines or as arrow glyphs. In the exploration task the haptic feedback reminds the feeling produced when one put his finger into a flow: vectors act upon fingertip, dragging it in the same direction as the local flow field. If a user does not oppose the movement, his hand describes a flow line within the vector field.

To overcome limitations that were facing pure graphical rendering techniques in the visualization of shock waves, Lawrence et al. in [12] directly render the gradient of the density field as a force feedback. Using this method, free motion is allowed in regions having low density (regions without shock), while within the shock regions, forces applied to the user result in behavior similar to a ball on a hill. Moreover, thanks to the haptic feedback the user can be alerted on the presence of any secondary shock (even invisible) contained in the main one.

In the same way, the vorticity (local curl of the velocity) is directly rendered as a torque to the user in Lawrence [12]. With this approach, properties like the local vortex of the flow field can be analyzed by the mean of the haptic channel. However, one notes that in the case of unsteady flows, since the curl may not convey the presence of vortices, the haptic feedback in these regions does not reveal relevant information about the vortex core.

To take advantage of a directional constraint, Itkis et al. [9] provide intuitive exploration modes for volumetric data sets. Their work provides a unified framework for different data modalities and effects such as texture and friction by the meaning of several motion rules and transfer functions. Thus to guide the user in a flow field, the proxy can be constrained along a streamline. In the same way, Baxter et al in [4] present a method for the haptic display of an incompressible Navier-Stokes fluid simulation. The proposed approach is then integrated into a painting application to enable the feeling of the fluid.

## 3 PRELIMINARIES ON CRITICAL POINTS

The literature of flow visualization counts two main groups of approaches, namely direct flow visualisation and feature-based rendering [7]. In direct flow visualisation, the entire data set is directly conveyed to the user by the mean of visual cues. In feature-based rendering methods, only data resulting from a pre-computation step (the features) are rendered to the user. In this last group of flow visualization techniques, one denotes topology based approaches which aim at detecting and classifying critical points of the flow, defined as the location where the velocity vanishes. Such points are of primary importance as they structure the overall flow features since they are constitutive of the flow topology.

In 2D and 3D flow, the eigen analysis of the Jacobian of the velocity field indicates the behaviour of the flow in the neighbourhood of critical points. This analysis indicates directions in which the flow approaches or leaves these regions [21]. In the

literature, critical points are classified as attracting or repelling node or focus, as saddle point, and center. (See Fig. 1.)

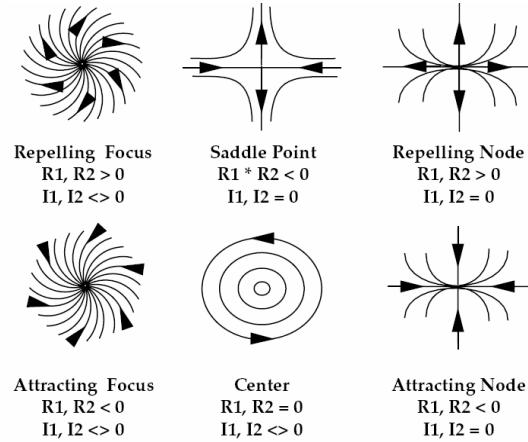


Figure 1. Classification of critical points of a 2D vector field according to eigenvectors [8]. Let  $R1, R2$  be the real parts of the eigen values and let  $I1, I2$  be the imaginary parts. For example, having  $R1$  and  $R2$  positive and  $I1$  and  $I2$  not null, corresponds to a repelling focus. On the other hand,  $R1$  and  $R2$  positive while  $I1$  and  $I2$  equal to zero correspond to a Repelling Node.

However, as mentioned by Theisel et al. [24], in the case of 3D time dependent flows (unsteady flows), there is still the need for an appropriate computation and analysis of these critical points. Moreover, Jiang et al. [11] note that there is paucity of methods that can tackle time varying (unsteady) data flow. In this document we present a user centered approach which aims at locating and analyzing 3D time dependent flow fields by taking advantage of the haptic rendering. The description of this contribution takes place in the next section.

## 4 CRITICAL POINTS ANALYSIS OF A 3D UNSTEADY FLOW

As mentioned previously, automatic exploration techniques are now facing great difficulties in the analysis of unsteady flow [24] [11]. However, one notes that scientists in fluid dynamics, thanks to their expertise and an important cognitive effort, may in some cases design a mind map of such flows. For this reason, we propose a framework which aims at assisting scientists in finding in real-time critical points where their analysis is focused, thus avoiding the time consuming process of computing a large number of such critical points.

Our approach presents an environment where experts can take advantage of their knowledge to achieve a work with less cognitive efforts than with conventional modes of presentation. Thanks to a multimodal and intuitive VR interaction, building the mind map of the flow is facilitated by a progressive construction of the final solution. The physicist starts with an empty virtual scene which will be completed throughout the exploration process of the unsteady flow. The proposed work addresses the analysis of a particular instant of the flow and can be applied to a time sequence without any changes. This approach can be summarized into two steps; the first one is devoted to the detection of critical points within the unsteady flow, while the second one characterizes the critical points highlighted in the first one.

The next two sections describe the localization and the characterization methods employed for this intuitive approach.

#### 4.1 Localization of critical points

In this subsection, we plan to localize in 3D space all the critical points of an unsteady flow by rendering a visuo-haptic feedback to the user. We know that the mapping of the field value onto a viscosity can allow a rapid scanning of a field. So we started by evaluating whether a viscosity inversely proportional to the magnitude of the velocity field can help in locating critical points or not. Unfortunately this feedback did not fill all our expectations in the tested system.

During the exploration process, when a user perceives the viscous feedback, he tends to slow down his motion in order to identify this region where could exist some critical points. However, since a viscosity is directly proportional to the motion of the user, the haptic feedback vanishes when the user stops his motion. This situation tends to confuse users. Because of that we have investigated a vibration feedback in order to alert the user on the presence of critical points.

Moreover, in order to facilitate the exploration process, the vibration feedback does not only depend on the explored point but also on the local volume surrounding the probe position. Since we are dealing with an irregular 3D grid, the explored volume corresponds to the local cuboid surrounding the haptic probe position. Using the local cuboid (Fig. 2), critical points are computed on the fly, at the local environment explored by the user. One notes that the expert is in this situation able to guide the detection of critical points. Because of his expertise, he may direct the exploration in areas of interest. He may thus at his rhythm construct his mind map of the flow.

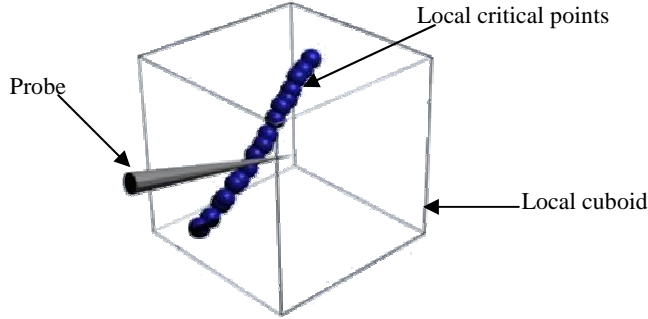


Figure 2. Representation of all the critical points located in the volume surrounding the probe position

To compute the critical points of an explored volume, for every couple of points within this volume we determine whether the magnitude of velocity field passes by zero between these two points. Due to the effectiveness of vibration feedbacks in alerting systems [13], whenever a critical point is detected in the explored volume, a vibration feedback is rendered to the user. In our VR platform, we used a Virtuouse™ 6 DoF haptic device. The vibration feedback is rendered by a unidirectional force on the fourth direction of the haptic device. It is defined by equation 1, where  $A$  represents the amplitude of the force feedback while  $w$  is the frequency and  $t$  the time:

$$F_w = A \cdot \sin(w \cdot t) \quad (1)$$

To prevent any disturbance in the exploration process, the vibration feedback is very smooth (in our implementation the amplitude is equal to 0.5 Newton and the frequency 200 Hz).

Using the proposed metaphor, while exploring the data volume, a vibration feedback allows users to be informed on the

presence of critical points in the explored volume. Figure 2 shows the critical points of an explored region. Since in the second step of our method we will identify and haptically display the nature of all the critical points currently detected, all the identified points are rendered graphically to the user in addition to the vibration feedback provided during this first step.

#### 4.2 Characterization of critical points

This step is devoted to the analysis of the neighbourhood of critical points detected in the previous subsection. The goal of this analysis is to identify Repelling and Attracting Focus, Repelling and Attracting Nodes, Saddle Points and Centers.

Since the critical points are rendered visually, the user can easily approach such regions, in order to analyze the behavior of the fluid around these areas of interest. To facilitate the initial positioning on a critical point, the user is attracted by a force  $F$  defined by equation 2. Let  $P$  be the probe position and  $C$  the critical point that we want to approach. The attraction  $F$  is defined as follows:

$$\vec{F} = \overrightarrow{PC} \quad (2)$$

Thereafter, once the expected position is reached, the velocity of the flow field is directly mapped as a force feedback to the user [10] [6]. In the implemented system, the mapping function is defined by equation 3, where  $\alpha$  is the coefficient of the mapping, and  $V$  the velocity of the flow:

$$\vec{F} = \alpha \cdot \vec{V} \quad (3)$$

As mentioned by Durbeck et al., this metaphor is analog to the feeling produced when one put its finger into a flow. If the user does not oppose the force feedback, the haptic device describes the trajectory of a fluid. In addition to the haptic feedback, to reinforce the perception of the fluid behavior the trajectory of the haptic probe is also rendered via the visual channel. Information such as the curvature of the trajectory is thus highlighted via the haptic feedback while the visual one can provide a global rendering about the trajectory. Figure 3 exhibits the trajectory of the haptic probe in a specific region of the cavity.

By using these two rendering channels, the user may thus characterize all the critical points detected in the first step.

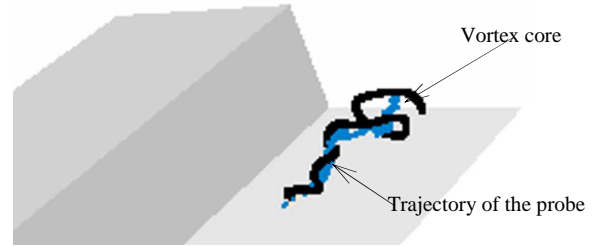


Figure 3. Representation of the trajectory (black) described by the probe around a vortex core (blue) in a cavity.

### 5 EXPERIMENTATION AND EVALUATION

In the previous section, we detailed a method aiming at taking advantage of the haptic rendering for the analysis of an unsteady flow. Through the two steps of this approach, we first described how to locate critical points, and then depicted the

characterization of these critical points. In the current section, we plan to assess the effectiveness of the haptic cue in this approach, investigate whether one can achieve better performances when guided by both Visual and Haptic cues (V+H) than with the visual (V) feedback only.

We describe two experiments ( $E_1$  and  $E_2$ ) in a VR immersive context using the EVI3d framework [5]. For visual information, we exploit a head tracking system to provide an active stereoscopic display on a large screen. The haptic feedback is obtained via a Virtuoso<sup>TM</sup> 6 DoF device.

For the evaluation, we used a data set resulting from a cavity flow simulation. This data set is composed by a 3D rectilinear grid of velocities of size 259x127x128 units. Figure 4 exhibits some streamlines representing the motion of the flow in the cavity at a specific instant of the simulation. For the experiments we used two different instants ( $T_1$  and  $T_2$ ) of the simulation.

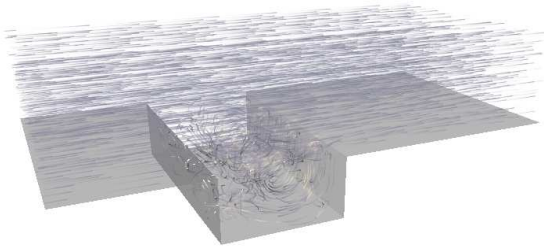


Figure 4. Visualization of an instant of the flow with some illuminated streamlines. On the middle of the cavity one can observe some swirls which denote the presence vortices.

Twelve participants, aged from 22 to 35, took part in the present study. Among them one counts 5 researchers in haptic, 4 researchers in fluid mechanics, the 3 others are working in the computer graphics field. Only 6 of them had previous experiences with haptic devices. Subjects were randomly allocated into two groups ( $G_1$  and  $G_2$ ) of 6 persons. To minimize any learning effect, members of  $G_1$  performed experiment  $E_1$  then  $E_2$  on the  $T_1$  data set in the (V) context then performed  $E_1$  then  $E_2$  on the  $T_2$  data set with the (V+H) environment. Members of  $G_2$  are evaluated on the opposite configuration.

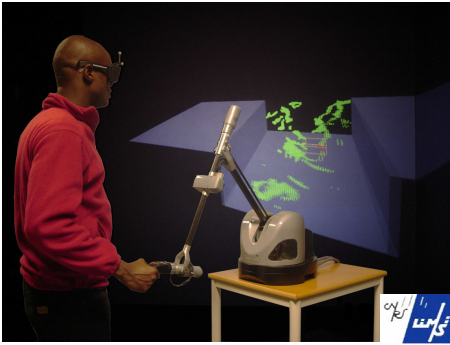


Figure 5. A user is exploring the unsteady flow of the cavity in a VR environment (first experiment)

## 5.1 Experiment 1: Localize all the critical points ( $E_1$ )

This experiment aims at evaluating the benefits of the haptic cue in the location of the critical points of an unsteady flow.

### 5.1.1 Experimental Condition

In the pure visual version (V) of the experiment, while exploring the cavity, whenever a critical point is detected in the cuboid surrounding the probe position, a 3D point is rendered on the screen. To allow users to have a good understanding related the spatial distribution of detected points, those located inside the cuboid are red while the others are green.

In the haptic-enhanced version, the visual rendering described previously is reinforced by the haptic one. As mentioned in section 4.1 a vibration feedback is exploited to alert the user on the presence of critical points located in the cuboid.

### 5.1.2 Experimental Procedure

Before each experiment, the participant is informed about the goal of the experiment, and also about available feedbacks and their meaning. Thereafter, he is invited to explore the cavity in order to discover all the critical points of the flow.

After the completion of the experiment we asked users whether they perceive any difference between the visual (V) and the haptic enhanced (V+H) version. In the case of a positive answer they are invited to note this difference. In this notation “1” represents a minor difference while “5” denotes the biggest one.

The strategy employed by the user during the exploration process is also investigated. We asked them whether the exploration is facilitated or not in the haptic-enhanced (V+H) version.

### 5.1.3 Data Analysis

With questions described in the previous subsection, we aim at evaluating whether participants judge that haptic cues may bring something new in the exploration process. To evaluate whether they achieve better performances in the haptic enhanced version, we record the trajectory described by the participant during the process.

## 5.2 Experiment 2: Characterize critical points ( $E_2$ )

This experiment plans to appraise whether the haptic feedback can improve or not the understanding of how the field enter and leave a critical point.

### 5.2.1 Experimental Condition

Critical points computed in the first experiment ( $E_1$ ) are rendered graphically in the scene. In the visual only version (V) of the experiment, the user has to position the probe on a critical point. To facilitate this positioning, their color changes from green to red when approaching the expected points. Thereafter, just by clicking, a streamline seeding from the critical point neighborhood is graphically rendered in the virtual scene.

In the haptic-enhanced version the user's hand is first attracted by critical points situated in the local volume surrounding the probe position (see equation 2). Once the critical point is reached, the velocity of the flow is directly rendered to the user as a force feedback (see equation 3).

### 5.2.2 Experimental Procedure

After a brief description about the metaphors that will be used in the experiment, participants are invited to analyze critical points. In the haptic-enhanced version, they are also instructed to not oppose the movement of the haptic device.

As in experiment 1, at the end of the experiment participants are invited to rank (from 1 to 5) any eventual difference perceived between the visual (V) and the haptic-enhanced (V+H) version.

Moreover we asked them about their strategy to approach critical points in an efficient manner in the pure visual (V) version.

### 5.2.3 Data Analysis

To assess whether haptic cues facilitate or not the positioning on a specific critical point, we record the distance between the position where participants click and the expected critical point.

## 5.3 Results and Discussion

### 5.3.1 E<sub>1</sub>: detection of critical points

Most of the participants have noted a clear difference between the two methods employed for searching critical points: (V) and (V+H). In the figure 6, one can read that more than 50% of participants have attributed the note of (3/5), and only 2 of them (less than 17%) have respectively noted 1/5 and 2/5.

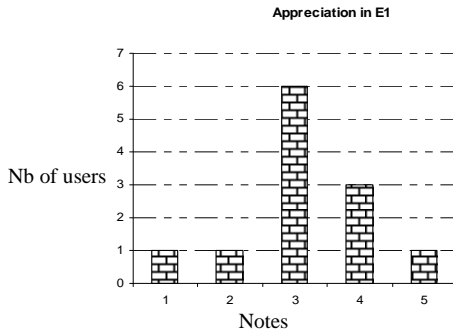


Figure 6. Notes of the users about the two versions of the first experiment

Through the second question, they had an opportunity to explain this difference. All emphasized that the haptic-enhanced version offers a better interaction. Thanks to the haptic cue that reinforces the visual feedback, users are more immersed in the virtual scene. In addition, they unanimously indicated that vibration cues really assisted them to rapidly detect areas of interest. Conversely, in the case of the pure visual feedback, they randomly explored the cavity in search of critical points. The visual rendering augmented by vibration cues enhances greatly the perception of critical points.

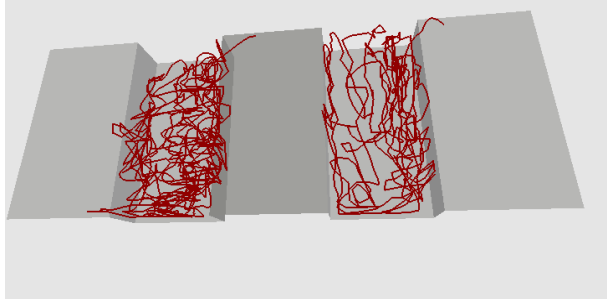


Figure 7. Representation of the trajectories described by user in the exploration process. In the left part represents the trajectory in the pure visual version, while the right one exhibits the haptic enhanced one.

As one can appreciate it on figure 7 which retraces the route of a user in an exploration process, in the haptic-enhanced version the trajectory looks to be more concentrated in some specific

regions, while in the pure visual one it seems to be quite bumpy. During haptic-assisted exploration movements of the user are not randomly realized, but are rather oriented towards areas of interest. In such conditions one notes that the build of the mental map of the flow field is facilitated.

### 5.3.2 E<sub>2</sub>: Characterization of critical points

More than 50% of the participants have highlighted a huge difference between the two versions of the second experiment (Fig. 8). 7 users estimate that this difference is worth 4 on a scale varying from 1 to 5. 2 of them estimate it about 2 while 2 others think that is full (5/5). Let us briefly summarize opinions of participants related to this experimentation.

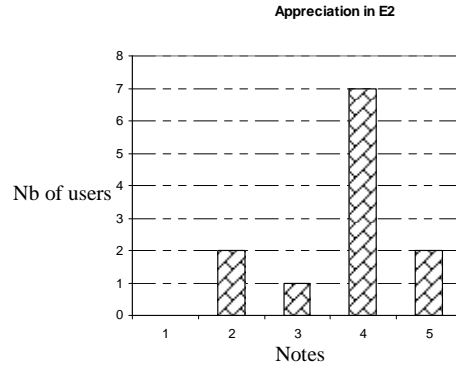


Figure 8. Notes of the users about the two versions of the second experiment

For some participants, being able to perceive the velocity of the flow through the haptic modality and to describe the trajectory of a fluid particle allows an interactive analysis of the critical points (as opposed to the static display of a streamline). They note difficulties faced at attempting to understand the temporal evolution of some serpentine (sinuous) streamlines.

More than 33% of the subjects highlighted that both methods (visualization of streamlines and haptic perception of the critical points' features) may be useful to analyse flows, while streamlines offer a suitable tool for a global comprehension of a flow.

These results show that haptic rendering gives access to local information related to the geometry of the streamline (curvatures). Moreover, it provides a better perception of elements of the vector field (amplitude and orientation). On the other hand, the visual feedback informs mainly about global aspects of the streamline.

Finally, one notes that the users unanimously indicated that the haptic feedback has facilitated the positioning on critical points. In the case where they did not have any haptic cue, much more concentration was required to locate critical points. On the recorded data, we note that the distance, between the expected point and the point where the user clicks, was ten time less in the haptic enhanced version than the pure visual version. As one can expect, the haptic feedback has once more proved being very useful in locating points in 3D space. Moreover, since the positioning is facilitated in the haptic enhanced version the user can thus concentrate on his goal and achieve a better understanding of the flow.

## 6 CONCLUSION AND FUTURE WORKS

In this paper we proposed an approach for the analysis of an unsteady 3D flow. We have thus exploited the haptic channel to facilitate the location and the characterization of critical points. With the vibration scheme we alert users about critical points

located in the local volume surrounding the probe position. Thereafter, we map the flow velocity as a force feedback in order to make possible a perception of the characteristics of the critical points detected in the previous step.

Experiments undertaken in a VR immersive environment confirmed the effectiveness of the proposed approach. Moreover, one notes that the haptic rendering reinforces (vibrations vs. visual indications) and supplements (haptic conveying of the velocity) effectively visual cues.

Moreover, this contribution has confirmed the presence of a vortex core inside the cavity spanwise direction. In a near future, we plan to extend our approach to other instants of the flow. We should thus be able to investigate the time evolution of the vortex cores and characterize their dynamical features.

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