THE ORIGIN OF THE PLUNGING PRESSURE FLUCTUATIONS FOR A SWIRLING FLOW WITH PRECESSING VORTEX ROPE IN A STRAIGHT DIFFUSER

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ABSTRACT

The paper attempts to elucidate a rather unexpected feature of the unsteady pressure field resulting from the self-induced instability of the decelerated swirling flow in a straight diffuser. We perform a numerical experiment using an axisymmetric surrogate draft tube, with inlet swirl corresponding to the flow exiting a Francis turbine runner when operating at 70% the best efficiency discharge. The numerical results correctly capture the precessing helical vortex (vortex rope), but they also reveal a complex dynamics of the vortex filament during the precession. We show that the vortex filament is stretching, leading to an elongated rope, followed by a sudden break up and a bouncing back phase. This cycle, with lower frequency that the precession one, appears to be responsible for the plunging (synchronous) pressure fluctuations superimposed over the rotating (asynchronous) pressure field associated with the precession of the vortex rope. As a result, we show that the plunging oscillations are not necessary the result of the interaction between the vortex rope and the draft tube elbow, but they are an intrinsic feature of the helical vortex filament dynamics.

KEYWORDS

Vortex rope, draft tube, pressure pulsation

1. INTRODUCTION

The dynamics of the rotating vortex rope in the discharge cone of Francis turbines operated at partial discharge has been extensively studied both experimentally and numerically [1]. Such studies are primarily aimed at assessing the accuracy of three-dimensional unsteady turbulent flow simulations to reproduce the measured unsteady velocity and pressure fields. Since the numerical full three-dimensional flow simulations are very expensive, with respect to computing time and resources, simplified two-dimensional axi-symmetrical flow simulations [2] attempted to predict the occurrence of the precessing vortex rope without actually computing it. Dörfler et al. [3, Ch. 2] review the whole range of low-frequency phenomena in swirling flows, with particular emphasis for hydraulic turbines. It is remarkable that the plethoras of draft tube vortex phenomena are presented for various discharge values (with respect to the best efficiency discharge). When analysing the wall pressure fluctuations [4] the pressure signal can be represented as the superposition of synchronous (plunging), asynchronous (rotating) and random components. In particular, the operating regime at 70% the best efficiency discharge, similar to the one investigated by Ciocan et al. [1], displays

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strong asynchronous pulsations associated with the precessing vortex rope, as well as a smaller synchronous component.

In this paper we attempt an explanation for the main cause of plunging oscillations in axisymmetric diffusers. According to Dörfler et al. [3, §2.2.11.2] such plunging pulsations should not be present since in conical draft tubes, without an elbow, there should be only asynchronous pulsations. However, our three-dimensional unsteady turbulent flow simulation in the axi-symmetrical domain defined in [2] clearly reveals synchronous (plunging) pressure pulsations. In Section 2 we describe the numerical experiment, and then in Section 3 we briefly present the procedure for extracting the vortex filament. Then, the vortex dynamics is analyzed in Section 4, and we summarize the preliminary conclusions in Section 5.

2. THREE-DIMENSIONAL UNSTEADY TURBULENT FLOW SIMULATION

A typical draft tube of modern hydraulic turbine, as shown in Fig. 1 left, has a conical diffuser followed by an elbow and a final diffuser with rectangular cross-section. Obviously, this three-dimensional geometry generates a complex flow, which heavily depends on the ingested swirling flow as generated by the turbine runner at various operating regime. Resiga et al. [2] considered a surrogate draft tube geometry by computing the equivalent hydraulic radius for each cross-section, thus obtaining the axisymmetric geometry depicted in Fig. 1 right.

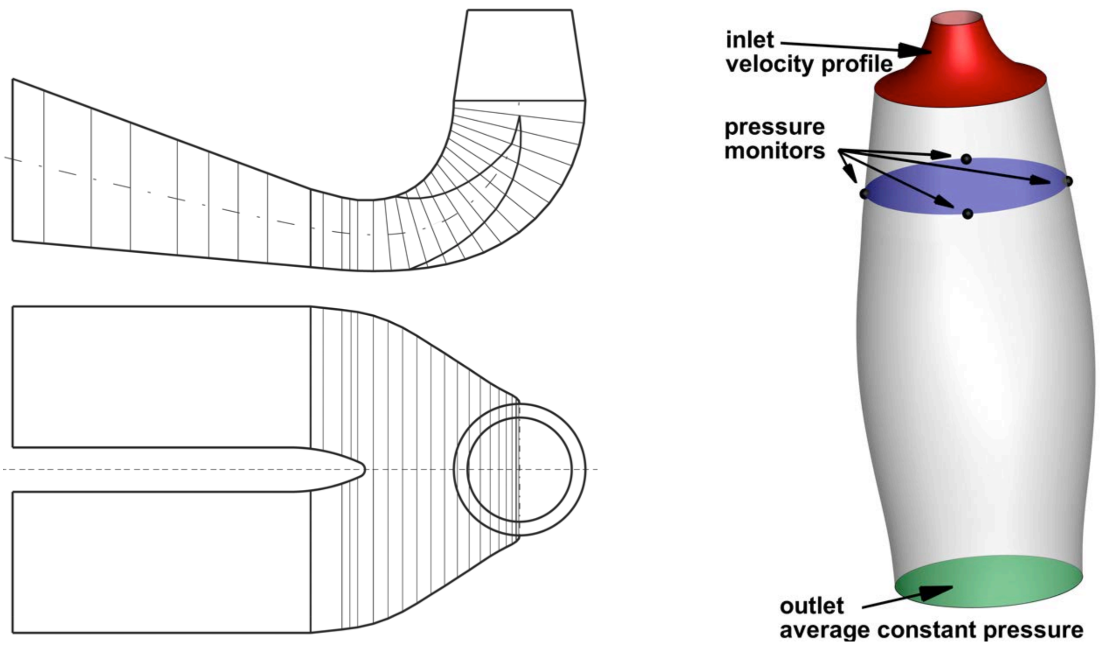

Fig. 1 The elbow draft tube (left) and the hydraulically equivalent axisymmetric domain (right).

The upstream part of the axisymmetric domain corresponds to the actual discharge cone, while the downstream part corresponds to the elbow region, up to the pier. The simplified version of the draft tube, Fig. 1 right, was reconstructed using the GAMBIT software and discretized with a block structured mesh of 1.5 million hexahedral cells.

The inlet section is chosen close to the runner blade trailing edge, and the inlet velocity components (axial, radial and circumferential), Fig. 2, as well as the turbulence quantities, were provided by Stein [5] who investigated this draft tube flow in his thesis [6].

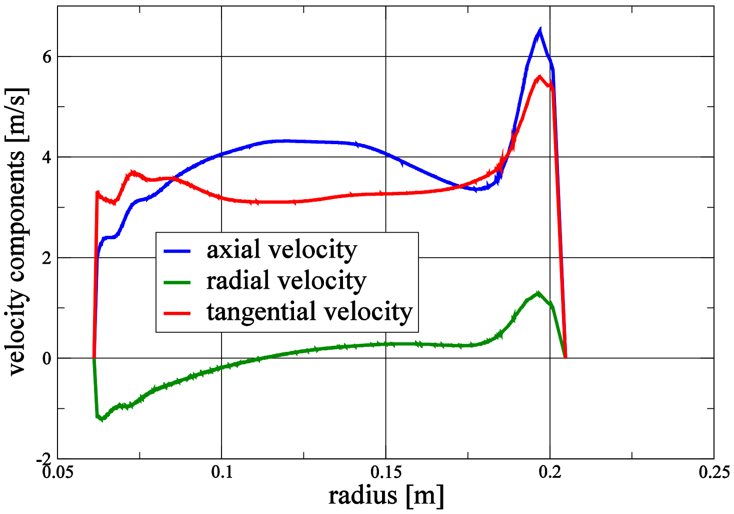

Fig.2 Velocity components distribution on inlet section of the draft tube.

A similar problem setup was considered by Foroutan and Yavuzkurt [7], who used the simplified draft tube investigated by Resiga et al. [8], and investigated several turbulence models: standard $k-\varepsilon$, realizable $k-\varepsilon$, shear stress transport (SST) $k-\omega$, and detached eddy simulation (DES) based on the SST $k-\omega$ Reynolds-averaged Navier-Stokes (RANS) model. According to [7] no considerable improvement in predictions is seen when applying different turbulence models. These studies showed that although they cannot capture the vortex rope, steady, 2D axisymmetric simulations can predict the occurrence and development of vortex breakdown with a central stagnant region in the draft tube. Moreover, as proved in [2], the vortex rope is precisely wrapped around this stagnant region.

The same inlet section shape, as shown in Fig. 1 right, with the inlet velocity from Fig. 2, has been used in [9] for three-dimensional unsteady elbow draft tube computations. Figure 14 from [9] shows that the obtained vortex rope has not only a precession but also suffers changes in shape as it rotates. Although this phenomenon can be attributed to the interaction of the vortex rope with the draft tube elbow, as suggested in [3], we show in this paper that it occurs in the simplified straight draft tube as well.

The present investigations employ the FLUENT 15 expert CFD software, using the Scale-Adaptive Simulation Method (SAS) introduced by Menter and Egorov [10]. An interesting and useful feature of the SAS approach is that for unstable flows the model changes smoothly from a large eddy simulation (LES) model through various stages of eddy-resolution back to a RANS model based on the specified time step. Menter and Egorov [10] claim that SAS is an advances unsteady RANS (URANS) model which can produce spectral content for unstable flows. A convincing set of complex examples of SAS applications is presented in [11]. Davidson [12,13] further compares the SST-SAS model with the standard SST-URANS model, confirming that the SAS term acts as expected: it reduces the turbulent viscosity compared to the SST-URANS model. As a result, the resolved fluctuations are much larger with the SST-SAS model than with the SST-URANS model.

The FLUENT 15 setup used in the present investigations uses SIMPLEC for pressure-velocity coupling method. For the spatial discretization we use *Least Squares Cell Based* for Gradient, *Second Order* for Pressure, *Bounded Central Differencing* for the Momentum, *Second Order Upwind* for Turbulent Kinetic Energy and Specific Dissipation Rate. The transient formulation was set to *Bounded Second Order Implicit*. The total flow time was more than 10 seconds, with a time step of 0.000167 seconds.

On the outlet we have used a pressure condition, with *average pressure specification* which allows the pressure on the outlet boundary to vary while maintaining an average equivalent to the specified value in the Gauge Pressure input field. Within this boundary pressure implementation, the pressure variation provides a certain level of non-reflectivity.

3. FLOW FEATURES EXTRACTION FROM NUMERICAL RESULTS

Vortices are readily identified by the rotating or swirling motion they create. Despite being easy to recognize, there is actually no formal mathematical definition to describe a vortex, and this lack of formalism has hindered the development of feature extraction techniques [14]. Vortices can be automatically detected using a technique developed by Sujudi and Haimes [15], which works on a cell by cell basis. It requires no user intervention and creates an effective visualization with a minimum of geometry. Let us summarize the vortex core extraction technique employed in this paper, as described in [16].

The velocity field $\mathbf{v} \equiv \mathbf{i}\, v_x + \mathbf{j} v_y + \mathbf{k}\, v_z$, which can be obtained for every node in the discretized volume, is commonly used to generate streamlines of streaklines. However, the velocity gradient tensor, $\nabla \mathbf{v}$, which provides the information on how velocity is changing in space, is rarely used for visualization purposes. This 3×3 tensor defined by

$$\nabla \mathbf{v} \equiv \begin{bmatrix} \partial v_x / \partial x & \partial v_x / \partial y & \partial v_x / \partial z \\ \partial v_y / \partial x & \partial v_y / \partial y & \partial v_y / \partial z \\ \partial v_z / \partial x & \partial v_z / \partial y & \partial v_z / \partial z \end{bmatrix}, \tag{1}$$

is not usually a quantity that is output by a CFD solver. However, the visualization expert software TECPLOT is computing it out of the FLUENT data. For $\nabla \mathbf{v}$ the eigenvalues $(\lambda_1, \lambda_2, \lambda_3)$ are the fundamental quantities which determine the qualitative flow pattern. In particular, we look for the cells with one real eigenvalue λ_r and a complex conjugate pair.

Vortices are automatically detected by using $\nabla \mathbf{v}$ throughout the mesh looking for situations of swirling flow. All mesh elements, in our case hexahedra, are broken into tetrahedron and the unique $\nabla \mathbf{v}$ is constructed and classified. If swirling, the direction orthogonal to the spiral plane (the eigenvector associated with λ_r) is used as the axis of the swirl. This direction is subtracted from the nodal velocities, and these reduced velocities are used to see if any faces display a zero. If so, that location on the face is marked. With at least two marked faces of the tetrahedron it is determined that the core center-line has pierced the cell. This algorithm is implemented by the routine FX_VORTEXCORE from the Fluid Feature Extraction Tool-kit[1] [17], which returns a set of vortex core segments with associated vortex core strength (vorticity magnitude) values. However, this technique still has some difficulties such as: i) not producing contiguous lines; ii) locating flow features that are not vortices; iii) sensitive to other non-local vector features [16]. Further advancements in the vortex core extraction techniques can be found in [18], [19].

Figure 3 shows the vortex core segments identified with the above algorithm implemented in the TECPLOT software. In Fig. 3a) one can easily identify the helical vortex line associated with the precessing vortex rope, as well as other spurious vortex segments further downstream. The vortex segments are colored by the vorticity magnitude, chosen as indicator of the vortex strength. One can remove the spurious vortex segments simply by setting a threshold for the vortex strengths, thus visualizing only the vortex rope, as shown in Fig. 3b). The correlation with an iso-pressure surface is shown in Fig. 3c). As expected, the

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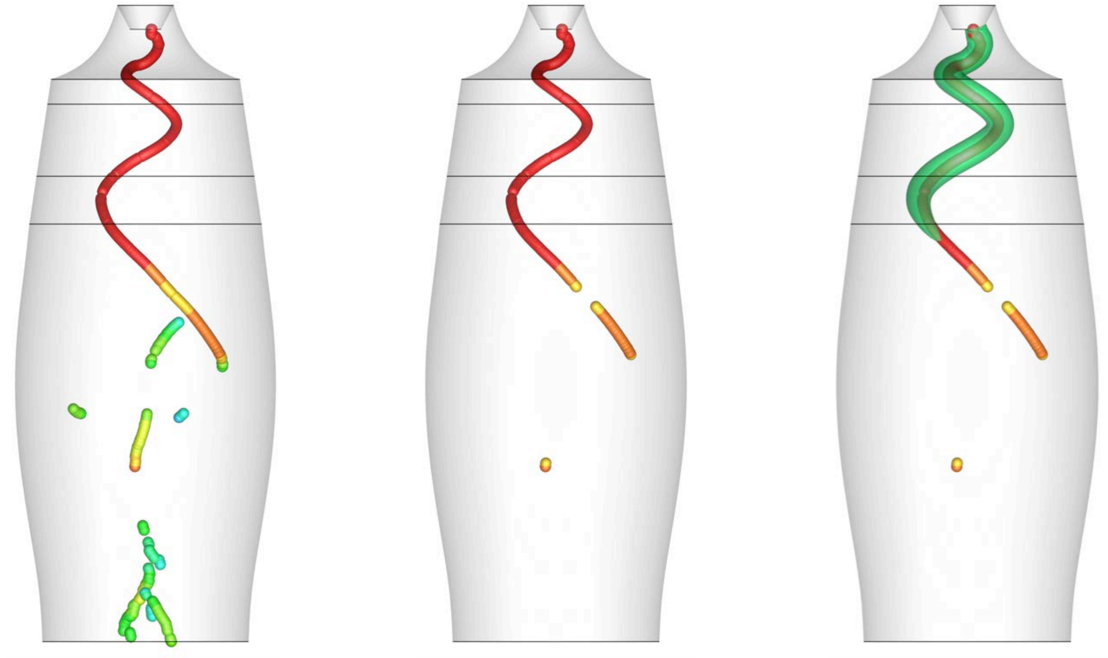
[1] FX – **F**luid feature e**X**traction tool-kit, http://raphael.mit.edu/fx

iso-pressure surface includes part of the vortex filament, but not all of it. Moreover, the extent of the iso-pressure surface depends on the chosen pressure value, while the vortex filament detection does not require any arbitrary parameter.

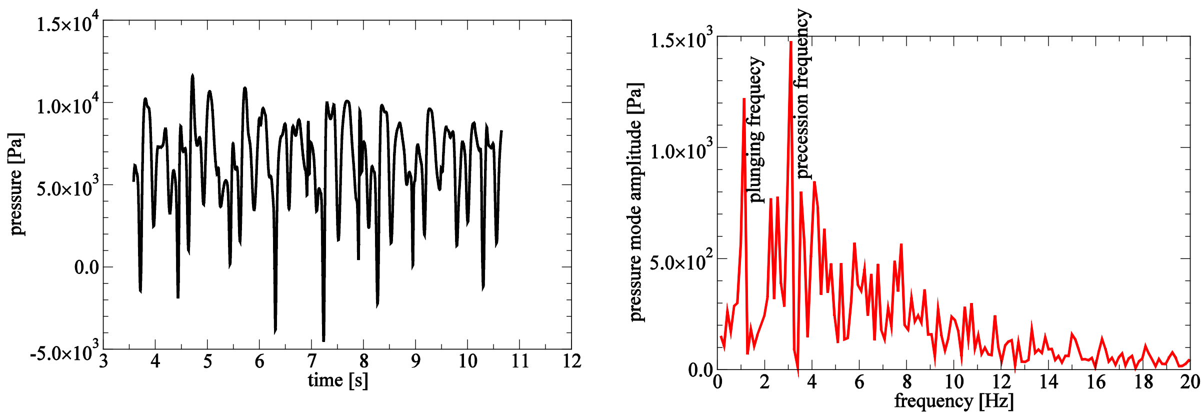


a) All vortex filaments *b) Blanked vortex filament* *c) Iso-pressure surface*

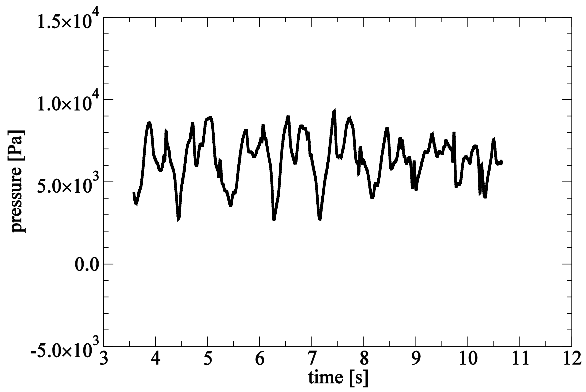
Fig. 3 Vortex filament extraction and correlation with iso-pressure surface.

4. THE PRECESSING VORTEX ROPE DYNAMICS

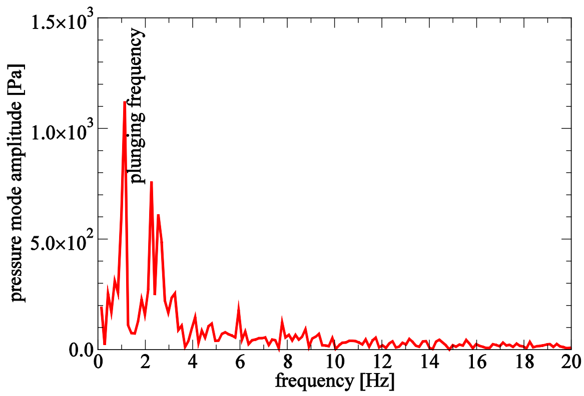
We start our analysis by examining the wall pressure fluctuations recorded at the pressure monitors shown in Fig. 1 right, as well as the average pressure on the wall circle where these monitors are located. When looking at the individual unsteady pressure monitors, the signal shown in Fig. 4a) shows in the Fourier spectrum, Fig. 4b), two distinct peaks: the first one corresponds to the precessing frequency of the vortex rope, in agreement with experimental and numerical data from [1, 9], and the second one, with lower frequency, corresponds to the plunging oscillations. This conclusion is supported by the analysis of the circle-averaged pressure, shown in Fig. 4c), which displays in the Fourier spectrum, Fig. 4d), the unaltered peak at low frequency.



a) Unsteady pressure at monitor *b) Fourier transform of monitor pressure*



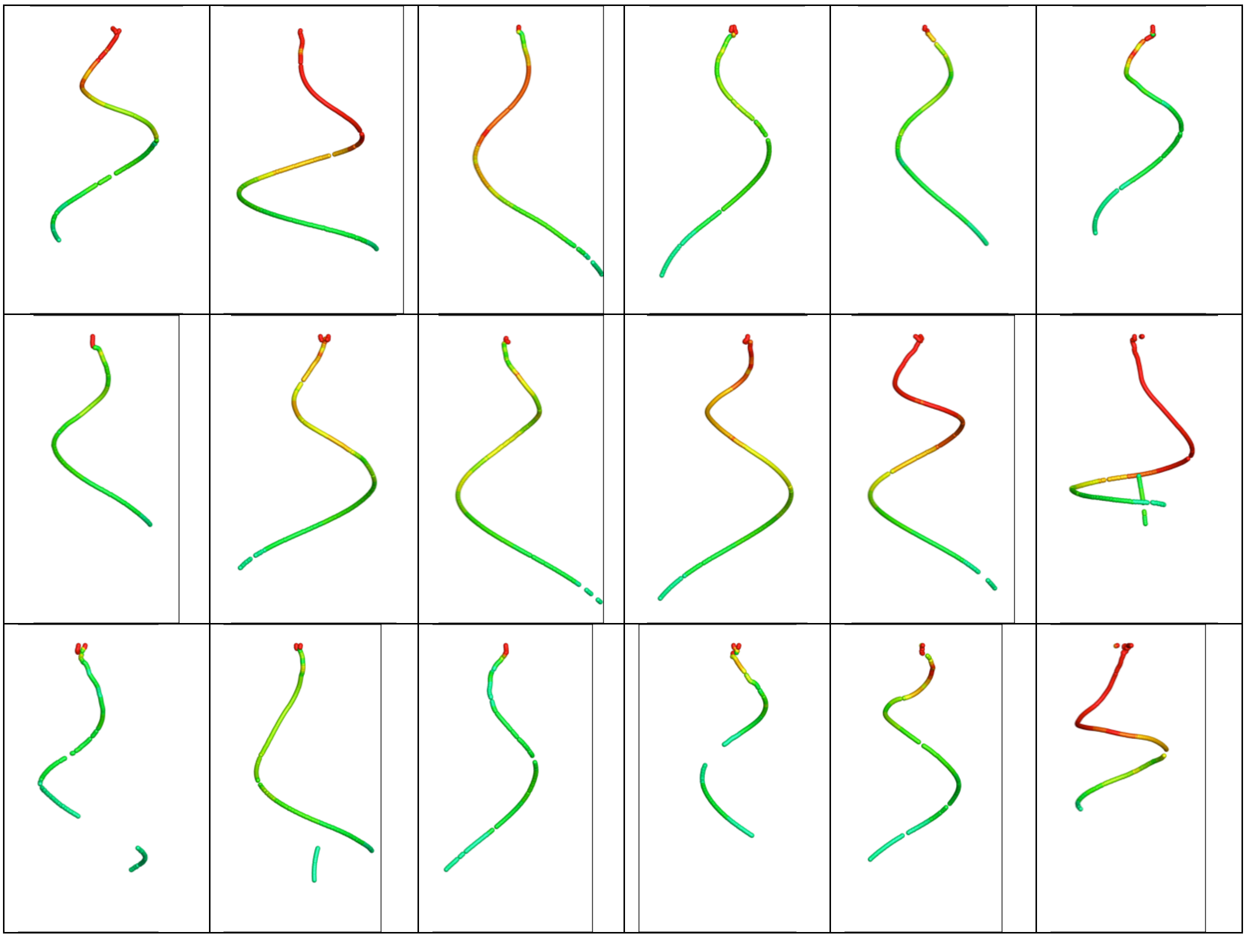
c) Circle-average unsteady pressure



d) Fourier transform circle-average pressure

Fig. 4 Unsteady wall pressure and its Fourier transform.

As a result, we conclude that plunging (synchronous) pressure pulsations occur in the straight axisymmetric geometry as well, and are not only the result of the interaction between the precessing vortex rope and the draft tube elbow. To further elucidate the flow mechanism that produces these plunging fluctuations we examine the evolution of the vortex rope filament as shown in Fig. 5.



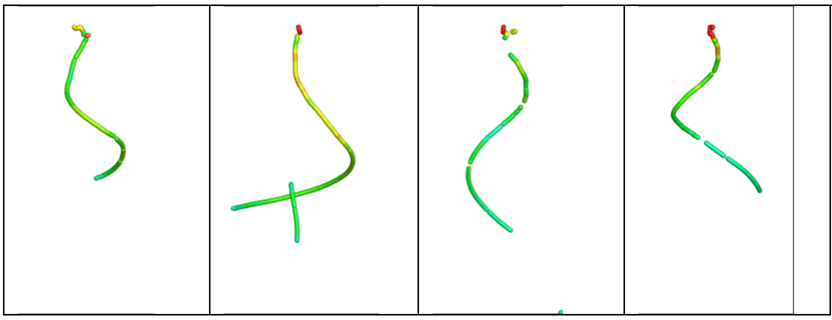


Fig. 5 Vortex rope filament dynamics: stretching, breaking, bouncing back sequence

Figure 5 shows significant changes in the vortex rope shape as it rotates with the precession frequency. One can identify an elongation phase, where the pitch increases and the vortex filament is stretched. Then, at the end of this stretching phase the vortex filament breaks up and the segment attached to the runner crown bounces back reaching a small pitch. The cycle is repeated with a smaller frequency than the precession frequency.

As a result, we conclude that it is this stretching – breaking – bouncing back sequence that leads to the low frequency plunging pressure fluctuations revealed by the Fourier analysis of the unsteady wall pressure signals.

5. CONCLUSION

The paper investigates the origin of the plunging (synchronous) pressure fluctuations is a straight axisymmetric diffuser. Although the inlet flow is steady and axisymmetric, the decelerated swirling flow develops a self-induced instability which evolves in the well known precessing helical vortex (vortex rope) with associated asynchronous (rotating) pressure fluctuations. By properly extracting the vortex core from the unsteady three-dimensional velocity field, we reveal a periodic sequence of vortex stretching, breaking up and bouncing back that appears to be responsible for the occurrence of the plunging fluctuations.

6. ACKNOWLEDGEMENTS

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8. NOMENCLATURE

v	[m/s]	velocity
λ		eigenvalue