Stabilisation of the swirl exiting a Francis runner far from the best efficiency point

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Abstract. The decelerated swirling flow in the discharge cone of Francis turbines operated at partial discharge, far from the best efficiency point, develops self-induced instabilities featuring a precessing helical vortex (so-called vortex rope) which hinders the stable and safe turbine operation. This is an intrinsic characteristic of the swirl exiting the Francis runner, which at part load has a relatively large residual flux of moment of momentum as well as an imbalanced specific hydraulic energy with an excess near the band. We address in this paper the question of how one should alter this swirling flow in order to mitigate further instabilities in the discharge cone. In doing so, we consider an actuator disk located in the upstream part of the discharge cone that model a runaway runner which alter the hub-to-shroud angular momentum and specific head distributions without altering the turbine operating point. However, such a runaway runner provides a swirl stabilisation further downstream thereby effectively mitigating the vortex rope.

1. Introduction
Francis hydraulic turbines are requested nowadays to operate within a wide range of discharge values while essentially keeping the same technical solution that is designed and optimized for the best efficiency regime. As a result, far from the best efficiency point flow instabilities develop in the discharge cone as a result of swirling flow deceleration. In particular, at partial discharge a precessing helical vortex (also called vortex rope) induces severe pressure fluctuations and power swings that hinder the stable and safe turbine operation [1]. Mitigating these self-induced instabilities is an active research topic including both theoretical studies on the self-induced instabilities root cause as well as development of practical solutions suitable for in-situ implementation.

This paper explores a methodology for altering the swirling flow exiting a Francis runner at partial discharge such that the flow instability in the discharge cone be mitigated. One hydrodynamically effective approach is to inject an axial water jet from the runner crown tip along the axis of the discharge cone [2] such that the central quasi-stagnant region is reduced or eliminated and the instability is removed. However, so far this solution did not lend itself to in-situ implementations in spite of the multiple successful laboratory tests. Recent stability studies [3] coupled with optimal control theory identified a theoretical body force distribution that successfully quenches the part-load vortex rope. The control jet proposed in [2], with its additional flux of axial momentum, acts in a similar way, but the
solution sought in [3] leans towards a runner crown appendage. In general, the flow instability is associated with the severe deceleration at and near the symmetry axis of the diffuser and the central quasi-stagnant region subsequently developed [4]. Basic studies on the vortex breakdown in decelerated swirling flows [5] reveal that one can eliminate the stagnant region by a small alteration of the upstream swirl profile in a diverging pipe. Instead of searching for solutions in the primitive variable space (velocity and pressure) it is more relevant to use the so-called generating functions – the moment of momentum and the specific head versus the streamfunction – in the Bragg-Hawthorne equation, which is the Euler equation for steady, axisymmetric swirling flows. It is shown in [5] that by reducing the imbalance of the specific head from the axis to the wall one can eliminate the vortex breakdown while keeping unchanged the discharge and the flux of moment of momentum, or in other words the turbine operating point. Such alteration can be done with a runaway runner installed immediately downstream the Francis runner, as it is sketched in Fig.1. We have used such a runaway (freely rotating) runner to de-stabilize a swirling flow and generate a precessing vortex rope in a laboratory swirl apparatus [6]. Why not using the same approach to stabilize the residual flow exiting the Francis runner at off-design operating points?

![Figure 1. The runaway runner downstream a Francis turbine runner for stabilizing the swirling flow ingested by the draft tube cone.](image1)

![Figure 2. The freely rotating Grim vane wheel downstream a marine propeller [7, Fig.13.3].](image2)

Similar technical solutions, although devised for a different purpose, have been developed for marine propellers as thrust augmentation devices [7, §13.2.2]. The so-called “Grim vane wheel”, Fig. 2, is a freely rotating bladed rotor installed behind the propeller that acts as a turbine on the inner part and as a propeller on the outer part, with vanishing net torque.

2. The problem setup
The setup of the case examined in this paper corresponds to an axisymmetric diffuser [8] with the inlet flow taken from an actual Francis runner operated at partial discharge. The variable radius pipe diffuser considered in this paper is shown in Fig. 3, with actual dimensions corresponding to a 400 mm diameter Francis runner model.
Figure 3. Axisymmetric diffuser with hydraulic radius variation from an actual draft tube. Computational domain in a meridian half-plane.

The corresponding 3D domain, Fig.4, with the same inlet swirl as for the 2D axisymmetric flow computations, has been considered in [9] to investigate the dynamics of the vortex rope beyond the precession motion. It is found that the helical vortex undergoes sequences of vortex stretching, snapping and bouncing back.

Figure 4. Three-dimensional axisymmetric diffuser with meridian cross-section in Fig. 1.

A survey section in the upstream part of the diffuser is shown in both Fig. 1 and Fig. 2, where experimental data for the axial and tangential velocity components are available. This particular location is also used in this paper as an actuator disc [10] to model a runaway runner that alters the swirl in order to mitigate the instabilities further downstream.

Section 3 of the paper presents some of our previous results that are the basis of the methodology for swirl modification without actually affecting the turbine operating point. Section 4 presents the numerical results with respect to the vortex rope mitigation, and the conclusions are summarized in Section 5.

3. Actuator disc model for the runaway runner
The main idea put forward in this paper is that the swirling flow ingested by the draft tube of a Francis turbine operated far from the best efficiency point can be altered by a runaway runner installed at the inlet of the discharge cone, in the neighborhood of the turbine throat. In order to design such a runner one must first determine the necessary changes in the swirling flow configuration which mitigate the vortex rope without affecting the turbine operating point.

Let us examine the flow with vortex rope using two different models. The first one corresponds to the axisymmetric swirling flow, detailed in [8], and the second one is the full 3D unsteady turbulent flow [9]. Figs. 5 and 6 show the numerical results for the axial and tangential profiles in the survey section, together with the experimental data measured with Laser Doppler Velocimetry. The experimental data are time averaged, while the 3D numerical data are circumferentially averaged. There is a good agreement between 2D/3D numerical data and the experimental ones particularly in the annular region of the main flow which is relevant for the following developments in this paper.
As shown in Fig. 7, the axisymmetric streamline pattern indicates the development of a central stagnant region in the upstream diverging part of the diffuser, with the actual vortex rope wrapped around this region [8, Fig.5]. The actual three-dimensional vortex rope is shown in Fig. 8 [9], being visualized both as a vortex filament (using the eigenvalues of the velocity gradient tensor [11]) and as an iso-pressure surface (as it is conveniently done for engineering simulations).

One can observe that the stagnant region shown in Fig. 7 is abruptly closing further downstream and the flow at the outlet section shows no vortex breakdown, with positive axial velocity. Noting that the outlet section has approximately the same diameter as the survey section, one could consider a flow configuration similar to the outlet one but immediately downstream the survey section. In other words, a runaway runner (which has zero net torque) installed in the region of the survey section should ingest the residual swirl as exiting the turbine runner and modify it to resemble the swirl in the outlet section of the diffuser, while keeping the same overall fluxes of the moment of momentum and total pressure, i.e. unchanging the turbine operating point.
Let us first recall that in axisymmetric flows one can introduce the Stokes’ streamfunction \([12]\) and the axial velocity component can be expressed as

\[
\rho V_a = \frac{1}{r} \frac{\partial \Psi}{\partial r}.
\]

(1)

The density is included in the streamfunction definition for consistency with the ANSYS-Fluent software (valid for compressible flows as well). The mass flow rate can be then easily obtained in any cross section as

\[
\dot{m} = \rho Q = \int_0^L \rho V_a 2\pi r \, dr = 2\pi \Psi_{wall}.
\]

(2)

For the case examined in this paper the volumetric discharge for the model turbine, measured on the test rig, is \(Q = 0.5245 \, m^3/s\) which, for the water density \(\rho = 998.2 \, kg/m^3\) gives \(\Psi_{wall} = 83.3 \, kg/s\) from eq. (2), as seen for the abscissa range in both Figs. 7 and 8. For a generic flow property \(\mathcal{F}\), its mass flow flux can be easily computed using the streamfunction as

\[
\int_0^L \mathcal{F} \rho V_a 2\pi r \, dr = 2\pi \int_0^{\Psi_{a,t}} \mathcal{F}(\Psi) \, d\Psi.
\]

(3)

In particular, the Euler equation for steady axisymmetric flows shows that both the moment of momentum \((rV_a)(\Psi)\) and total pressure \(p_{tot}(\Psi)\) are functional dependencies only on the streamfunction, as shown in Figs. 9 and 10, respectively.

![Figure 9](image-url) Figure 9. The functional dependence \((rV_a)(\Psi)\).

![Figure 10](image-url) Figure 10. The functional dependence \(p_{tot}(\Psi)\).

The fluxes defined in (3) correspond to the areas below the curves. The black lines correspond to the swirl at the survey section and the blue dashed lines correspond to the swirl at the outlet section, with a slight vertical shift to compensate the viscous losses, thereby preserving the fluxes. Wherever either \(p_{tot}\) or \(rV_a\) decreases one has the behaviour of a turbine (denoted as T), otherwise it acts as a pump (the P region). The algebraic sum of areas T and P vanishes.

Let us turn our attention to the actuator disc model, to be placed at the survey section indicated in Fig. 1 to emulate the effect of a runaway runner. The basic turbomachinery theory states that the jump in total pressure \(p_{tot}\) equals the jump in \(\rho \Omega r V_a\) on each axisymmetric streamsurface, or

\[
\Delta p_{tot}(\Psi) = \Delta \left( \rho \Omega r V_a \right)(\Psi), \text{ where}
\]

\[
\Delta p_{tot} = \left( p_{tot} \right)_{\text{downstream}} - \left( p_{tot} \right)_{\text{upstream}},
\]

\[
\Delta \left( \rho \Omega r V_a \right) = \rho \Omega \left[ \left( r V_a \right)_{\text{downstream}} - \left( r V_a \right)_{\text{upstream}} \right].
\]

(4)
Obviously, the mass flux of the two jumps vanishes by definition. However, the condition (4) is not precisely fulfilled for the blue dashed curves in Figs. 9 and 10. As a result, a rather minor correction is performed, as follows.

First, the runaway runner angular speed is found by at least squares fit between the two jumps above.

\[
\frac{d}{d\Omega} \sum_i \left[ \left( \Delta p_{\text{tot}} \right)_i - \left( \rho \Omega \Delta \left( r V_u \right) \right)_i \right]^2 = 0, \\
\Rightarrow \rho \Omega = \frac{\sum_i \left[ \left( \Delta p_{\text{tot}} \right)_i \left( \Delta \left( r V_u \right) \right)_i \right]}{\sum_i \left( \Delta \left( r V_u \right) \right)_i^2}
\]

For the data from Figs 9 and 10 the runaway runner angular speed is \( \Omega = 45.95 \text{ rad/s} \), or 438.8 rpm. For comparison, the model Francis runner considered in the present example had a speed of 750 rpm.

Second, corrected values for the jumps are computed as weighted averages

\[
\left( \Delta p_{\text{tot}} \right)_{\text{corrected}} = \alpha \Delta \left( \rho \Omega r V_u \right) + (1 - \alpha) \Delta p_{\text{tot}}, \\
\left( \Delta \left( r V_u \right) \right)_{\text{corrected}} = \alpha \Delta \left( r V_u \right) + (1 - \alpha) \Delta p_{\text{tot}}/\rho \Omega,
\]

where \( \alpha \in [0,1] \) is a weighting factor. Obviously, these corrected downstream values for \( \left( r V_u \right)(\Psi) \) and \( p_{\text{tot}}(\Psi) \) shown with red solid lines in Figs. 9 and 10 for \( \alpha = 1/2 \), respectively, exactly satisfy eq. (4).

### 3.1. Numerical implementation

The actuator disc model, which is a surrogate for the runaway runner, is implemented in ANSYS-Fluent commercial CFD code using the “User-Defined Fan Model” for the 3D unsteady turbulent flow simulation. The survey section is changed from interior-type to fan-type, and the radial profiles for the downstream tangential velocity and the static pressure jump (as required by the Fluent fan model) are prescribed. In order to compute these radial profiles, the inverse map \( \Psi \rightarrow r \) is employed.

The static pressure jump is computed from the total pressure jump, Fig. 10, by subtracting the dynamic pressure jump. Both the axial and radial velocity components are considered continuous across the actuator disc, although a refined methodology could consider a jump in the radial profile as well by employing the full actuator disc theory.

### 4. Numerical results for the swirling flow stabilized with a runaway runner

After the survey section shown in Fig. 8 is replaced by the actuator disc (modeled as fan in ANSYS-Fluent as shown in the previous section) the unsteady 3D flow significantly changes after a short period of time of 0.1 s (the time step of the numerical simulation is 0.2 ms). In this incipient stage, Fig. 11, the wellstructured vortex rope from Fig. 8 is on one hand already significantly attenuated and on the other hand it breaks down in many vortex segments.
The main result of the paper is illustrated in Fig. 12, at 0.5 seconds later that the flow-field shown in Fig. 11. One can see that the initial vortex rope from Fig. 8 is practically mitigated, with the well developed vortex filament broken down in a cloud of small vortex filaments. The flow region with such fragmented small vortices has a higher turbulence intensity but it no longer generates the high amplitude low frequency pressure fluctuations as the precessing vortex rope. It is expected that later on the swirling flow in the diffuser becomes even more stable, with an additional benefit of reducing the hydraulic losses and increasing the pressure recovery efficiency.

Figure 12. Advanced stage of mitigating the vortex rope from Fig. 8.

The stabilized configuration of the swirl downstream the actuator disc is shown in Fig. 13 after 5 seconds flow time (25000 time steps). One can see that the swirling flow is practically stabilized to a quasi axi-symmetrical configuration, with an effective mitigation of the vortex rope. Upstream the actuator disc the precessing vortex still develops, but the rather small re-balancing of the total pressure from the axis to the wall, as shown in Fig. 10, effectively removes the swirling flow instability. The downstream vortex filament is practically aligned to the axis, and there are no more pressure fluctuations as induced by initial precession helical vortex shown in Fig. 8. One can consider this numerical investigation as a successful demonstrator of the runaway runner concept for swirl stabilization.

Figure 13. Final stage of mitigating the vortex rope from Fig. 8.

5. Conclusions
The paper explores a novel concept for stabilizing the swirling flow downstream the Francis runner far from the best efficiency regime. Starting from the fact that the total pressure (specific hydraulic energy) excess near the band, with a corresponding deficit towards the crown, is the main factor leading to self-
induced instabilities in decelerated swirling flows, we explore a novel technique to reduce this energy radial imbalance.

From practical point of view we propose a runaway runner (axial-type runner) installed immediately downstream the Francis runner, at the draft tube inlet. Along the hub-to-shroud span the blades work on some segments as turbine and on the remaining part as pump, such that the overall torque vanishes at the self-adjusted runaway speed. The paper introduces a methodology for designing the flow downstream such a runaway runner, in preparation for a full inverse design if its blades shape.

By rebalancing the specific energy along the radius, without affecting the turbine operating point one can expect that the diffuser swirling flow becomes more stable and as a result the vortex rope be effectively mitigated. In order to verify this conjecture we perform a numerical experiment where the runaway runner is modeled as an actuator disc. By suitably choosing the jump in total pressure and the associated jump in moment of momentum, it is shown that the vortex rope is gradually de-structured, the well-defined precessing helical vortex filament is broken down as a cloud of random vortices, and essentially the vortex rope is effectively mitigated.

Further investigations will address quantitatively, including experimental, the reduction in pressure fluctuations, decrease of diffuser hydraulic losses and increase in pressure recovery, as well as the behavior of the runaway runner within a wide range of turbine operating points.

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