

Power break off in a bulb turbine: wall pressure sensor investigation

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Abstract. A measurement campaign using unsteady wall pressure sensors on a bulb turbine draft tube was performed over the power and efficiency break off range of a N_{11} curve. This study is part of the BulbT project, undertaken by the Consortium on hydraulic machines and the LAMH (Hydraulic Machine Laboratory of Laval University). The chosen operating points include the best efficiency point for a high runner blade angle and a high N_{11} . Three other points, with the same N_{11} , have been selected in the break off zone of the efficiency curve. Flow conditions have been set using the guide vanes while the runner blade angle remained constant. The pressure sensors were developed from small piezoresistive chips with high frequency response. The calibration gave an instrumental error lower than 0.3% of the measurement range. The unsteady wall pressure was measured simultaneously at 13 locations inside the first part of the draft tube, which is conical, and at 16 locations in the circular to rectangular transition part just downstream. It was also measured at 11 locations along a streamwise line path at the bottom left part of the draft tube, where flow separation occurs, covering the whole streamwise extent of the draft tube. For seven radial-azimuthal planes, four sensors were distributed azimuthally.

As confirmed by tuft visualizations, the break off phenomenon is correlated to the presence of flow separation inside the diffuser at the wall. The break off is linked to the appearance of a large recirculation in the draft tube. The efficiency drop increases with the size of the separated region. Analysis of the draft tube pressure coefficients confirms that the break off is related to diffuser losses. The streamwise evolution of the mean pressure coefficient is analyzed for the different operating conditions. An azimuthal dissymmetry of the mean pressure produced by the separation is detected. The pressure signals have been analyzed and used to track the separation zone depending on the operating conditions. Spectral analysis of these signals reveals a low frequency unsteadiness generated by the flow separation.

1. Introduction

The flow in a turbine diffuser is complex. First, the flow at the diffuser entrance is already disturbed by many flow phenomena such as blade and hub wakes and vortices coming from the runner. In addition, the flow is subjected to an adverse pressure gradient. The diffuser geometry determines in great part the pressure distribution. For instance, the opening angle of the diffuser is chosen to avoid flow separation at the wall and backflow [1]. The latter phenomena can reduce dramatically the pressure recovery and they have been observed in numerical studies of bulb turbine draft tubes [2] [3]. Low head turbines are strongly affected by draft tube performance.



Flow separation is an important practical and theoretical challenge. The classical view of flow separation is the two-dimensional one, with a well-defined separation point corresponding to zero wall shear stress. But the majority of flow separations are more complex because of their tridimensional and unsteady character [4] [5]. The global topology of three-dimensional separation has been intensively investigated using critical point theory [6] [7]. It has been found that three-dimensional separation corresponds to the convergence of skin friction lines [8]. The majority of studies on separation were performed in open area flows. In confined flows the situation is more complex because the separated zones can interact with other flow structures [9].

The Consortium on Hydraulic Machines and the LAMH, after the success of the previous research project, AxialT [10], have decided to better understand draft tube performance losses by investigating a specially designed draft tube of a bulb turbine, an investigation that is part of the BulbT project. The BulbT diffuser opening angle was intentionally chosen to be aggressive. As a result, the efficiency and power curves break off at high rotation speeds. A detailed investigation of flow phenomena in the draft tube has confirmed that the power and efficiency break offs are linked to the presence of flow separation at the wall inside the diffuser [11].

To obtain additional information on draft tube separation and its link to the break off phenomena, extensive unsteady pressure measurements have been performed for four operating conditions. These operating points (OP) are representative of different flow separation states. Fluctuating pressures have been measured accurately thanks to the use of unsteady flush-mounted sensors. Similar steady and unsteady pressure analyses have been performed in the past at the wall of different draft tubes [12, 13] and within the flow of an axial turbine with an unsteady pressure probe [14].

The next section presents the experimental setup and the operating conditions. Then, the effects of separation on time-averaged parameters like draft tube pressure recovery coefficient and dissymmetry coefficient are presented. In section 4, time-dependent analyses, with spectra of pressure signals, are used to track the separation zone. The last section combines the various results in order to propose a global perspective and some hypotheses about flow separation in the BulbT draft tube.

2. Experimental setup

The bulb-shaped turbine is supported by two vertical symmetric piers. The distributor has 16 guide vanes and the runner has four directional blades. As shown in figure 2a, the draft tube is composed of two parts. The first one is an acrylic cone with an opening half angle at 10.25° and with a length of 1.4 runner shroud diameter (D_{ref}). The second part, the transition part, is made in metal. It transforms the circular section into a rectangular section within a length of $2.3 D_{ref}$. The transition section is not symmetric. Right and left sides diverge with an angle of 9.5° , the top side is near horizontal and the bottom side diverges with an angle of 5° . Divergence angles are noted in red in the yz cut of figure 2a. Figure 2b shows the evolution of the area along the draft tube, where A_{ref} refers to the area define with D_{ref} . The cross-sectional area of the draft tube increases approximately by a factor 4 within the length of the draft tube ($L_{dt}, L_{dt}=3.7 D_{ref}$), and can be considered aggressive.

The parameters Q_{11} , N_{11} , P_{11} and η are used to describe the operation points:

$$Q_{11} = \frac{Q}{\sqrt{H} D_{ref}^2}; N_{11} = \frac{N D_{ref}}{\sqrt{H}}; P_{11} = \frac{P}{D_{ref}^2 H^{3/2}}; \eta = \frac{P}{\rho g H Q} \quad (1)$$

where N is the model rotation velocity (rpm), H is the net water head (m), Q is the flow rate (m^3/s), P is the mechanical power extracted (W), ρ is the water density (kg/m^3) and g is the gravitational constant (m/s^2).

To produce significant but representative flow separation and break off, the runner blade angle is set at 30.2° (the best efficiency point measured is at 22.5°). The unitary rotation speed N_{11} was set at 170 rpm, which is higher than the N_{11} with the best efficiency for a blade angle of 30.2° . The first operating point, OP 2, corresponds to the best operating point in terms of efficiency. The three other operating points selected correspond to overload conditions for which the efficiency breaks off, and so does the power for two of them. Table 1 and figures 1a and 1b describe the different operating points

analysed in this paper. The unitary power P_{11} , the efficiency η and the unitary flow rate Q_{11} have been normalised by the corresponding values for OP 2. The flow separation characterisation by tuft visualizations performed by [11] is summarised in table 1. Figures 1a and 1b respectively present the efficiency and power curves at $N_{11}=170$ rpm for the four operating points. No diphasic vortex rope has been observed for these operating points.

Table 1. Operating point and tufts results in the draft tube.

OP	Guide vanes	Efficiency	Power	Tuft visualizations
2	0°	Best OP		Small separation in the transition section
3	+1° v/s OP 2		Best OP	Large sporadic separations
4	+2.8° v/s OP 2	Break off	Break off	Large separation in both sections
5	+4.8° v/s OP 2	Break off	Break off	Large separation in both sections

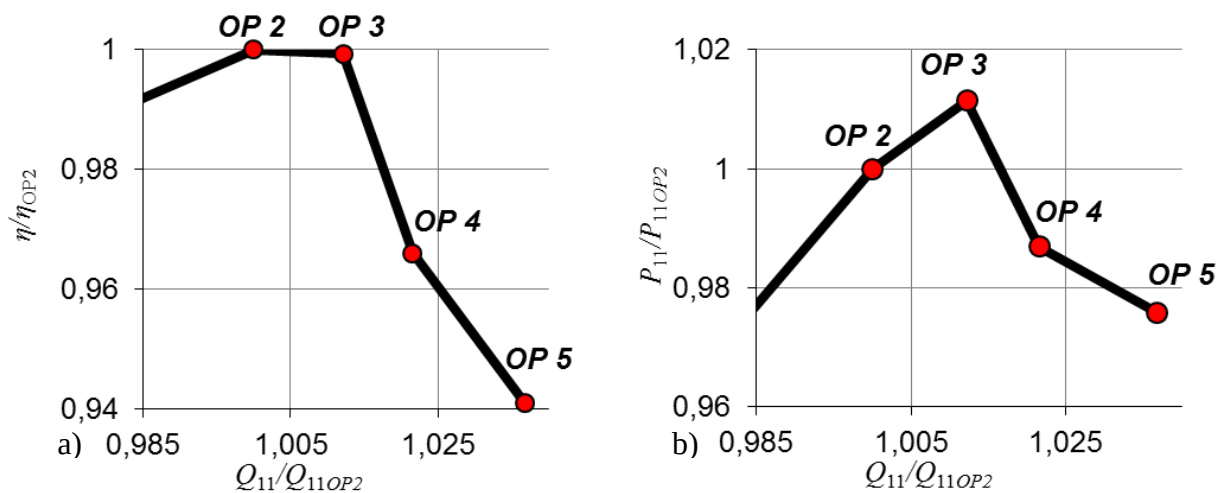


Figure 1. Respectively a) efficiency and b) power curve with the four selected operating points (OP 2 to 5)

A total of 29 sensors have been installed in the draft tube. The pressure sensors fabricated for this study are made of Unisensor piezoresistive ships mounted at the end of 4 mm outer diameter probes. Sensor power supply and signal conditioning are delivered by Meiri 520-AS conditioners having a maximal frequency range of 20 kHz. The acquisition is ensured by a National Instrument PCI-6036E acquisition card and the Labview environment. The static calibration gave an instrumental error lower than 0.3% of the measurement range. Thirteen pressure sensors were located inside the conical part and sixteen inside the transition section. Previous tuft visualizations [11] localise flow separation in the bottom and the x+ side of the draft tube (see figure 2c). The flow separation structure appears to be complex, turbulent and presents different time and spatial scales. The observed zone of backflow is principally located downstream of plane A4 (see figure 2c) but some backflow events are present as far upstream as plane A2. Eleven sensors are in this corner (L1-L11 on the red line in figure 2c) versus six for the other bottom corner. To characterise dissymmetry, six cross-sectional planes equipped with 4 sensors each, have been chosen along the draft tube (A1 to A6 in figure 2c). Plane A1 is approximately 25 mm downstream of the blades. Plane A2 is just after the hub end. Plane A3 is near the end of the conical part. Plane A4 is at the beginning of the transition section. Plane A5 is an intermediate plane inside the transition section. Finally, plane A6 is at the transition section exit.

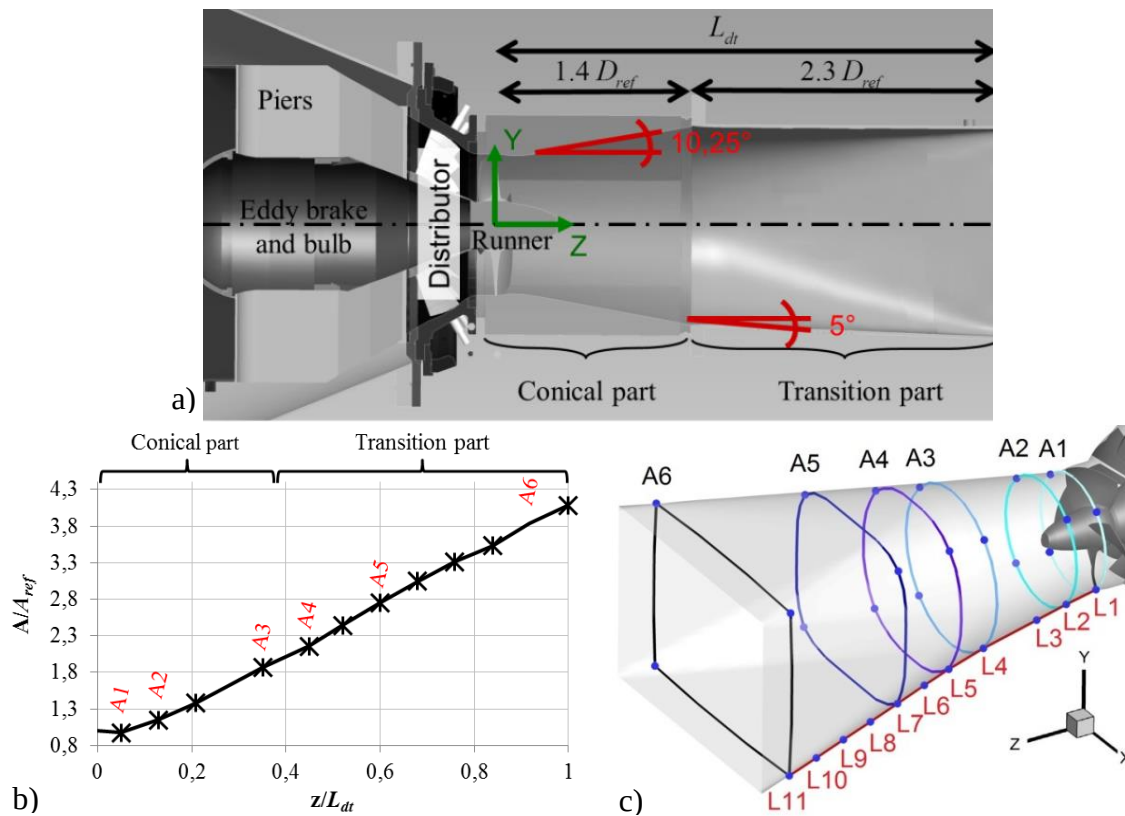


Figure 2. a) Bulb turbine sketch, , c) Area evolution along the draft tube, b) Sensor positions and BulbT Axis.

3. Time-averaged pressure results

All the time-averaged parameters have been obtained with 600 000 realisations at 1 KHz.

3.1. Pressure recovery coefficient

The pressure recovery coefficient C_p is defined as

$$C_p = \frac{P_{A1} - P}{P_{dyn A1}} \text{ and } P_{dyn A1} = \frac{1}{2} \rho \left(\frac{Q}{A1} \right)^2 \quad (2)$$

where $A1$ is the entrance section area (m²), ρ is the water density (kg/m³), Q is the flow rate (m³/s), P_{A1} is the average of the four azimuthal mean pressures for plane $A1$ (Pa) and P is the average of the four azimuthal mean pressures for plane A (in figure 3a) or the pressure along L (in figure 3b) (Pa).

Figures 3a and 3b show that, for all operating points, the pressure recovery inside the conical part represents more than 85% of the total recovery. The pressure recovery inside the conical part is 86% for OP 2 and 3, and respectively 88 and 89% for OP 4 and 5 at $A3$. However, the total pressure recovery is about 5% and 8% lower at OP 4 and 5 respectively. Since a large part of the total head is contained in the draft tube pressure recovery [11], all loss phenomena inside the conical part have an important impact on turbine performance. This is the case for OP 4 and 5 as can be seen with the efficiency and power curves, in figures 1 and 2 respectively.

As expected, operating conditions with large flow separation (OP 4 and 5) have a worst pressure recovery than operating conditions without or with sporadic separation (OP 2 and 3, table 1). The distribution in figure 3b is along the corner where flow separation occurs. For OP 5, the reduction

begins earlier than for OP 4. This effect is probably due to the fact that the separation zone extends further upstream as the guide vanes are opened.

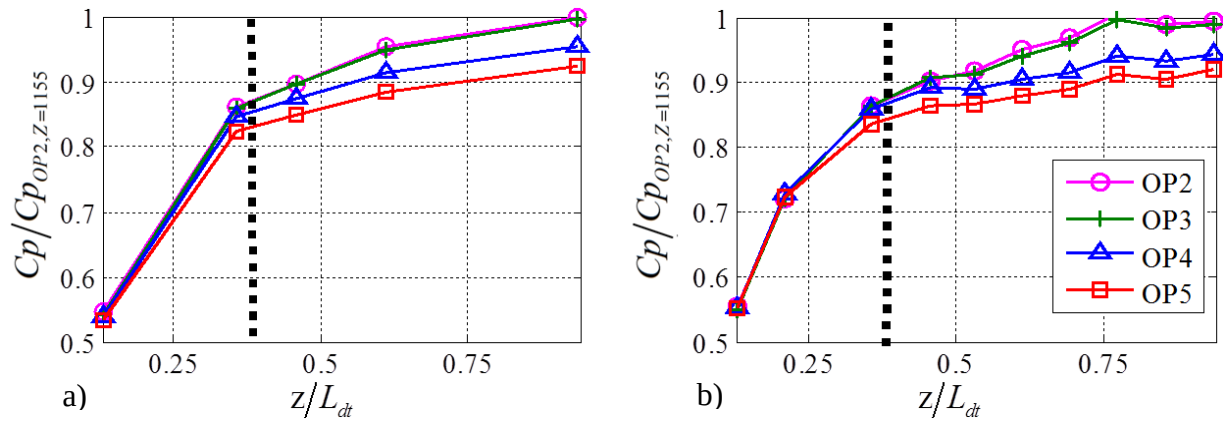


Figure 3. Respectively a) the normalized pressure recovery coefficient, C_p , at the various cross-sectional planes A, and b) the normalized C_p along the line L for the different OPs. The black line represents the limit between cone and draft tube. C_p is normalised by the maximum C_p value for OP2. Lines connecting data points are only for visual aid.

3.2. Azimuthal dissymmetry of mean pressure

In order to estimate the degree of azimuthal dissymmetry of the mean pressure at each cross-section A, a pressure dissymmetry coefficient is defined as follows:

$$\Delta C p_{dissy} = \left(P_{(x,y)} - \frac{1}{4} \sum_i P_{(x_i, y_i)} \right) / P_{dyn} \quad (3)$$

where $P_{(x,y)}$ is the pressure at corner (x,y) and P_{dyn} is the estimated dynamic pressure at the corresponding cross-section A. A positive (negative) $\Delta C p_{dissy}$ represents an excess (deficit) of pressure in comparison to the average of all four corner pressures. Figure 4 presents the dissymmetry coefficient for the cross-sectional planes A3 to A6. The black contours represent the geometrical sections. Diagonal lines are scales of $\Delta C p_{dissy}$ with a graduation corresponding to 0.05. Over-pressure has been represented outside the section and under-pressure inside the section.

For the first two planes, A1 and A2, the difference between operating points is negligible. Separation, which occurs further downstream for all OPs, does not have a strong influence on the pressure dissymmetry on the first part of the conical section of the draft tube.

Planes A3 and A4 are at the end of the conical section and at the beginning of the transition section of the draft tube. Here the difference between operating points becomes more appreciable, in particular in the opposite corners (x+,y-) and (x-,y+). In the corner (x+,y-), OP 2 exhibits small pressure dissymmetry while OP 3, with sporadic separation, leads to an overpressure at that corner. For operating points with large separation regions in the conical part, OP 4 and 5, the overpressure in the corner (x+,y-) is even more important, and an under-pressure is now present at corner (x-,y+).

Pressures in plane A5 at the upper part of the draft tube are similar for all operating points, with an overpressure in (x-,y+) and under-pressure in (x+,y+). For OP 2, the pressures are similar in the bottom corners. For the other operating points, the flow is in overpressure in the corner (x-,y-) and under-pressure in corner (x+,y-). The normalised level of under-pressure in this corner is smaller for OP 5 than for OP 3 and 4. At plane 6, the bottom part exhibits similar trends for OP 2, 3 and 4, with overpressures on the x- side and under-pressures on the x+ side. This pressure dissymmetry pattern increases with flow separation extension. For OP 4, the pressure dissymmetry coefficient difference between corner (x-,y-) and (x+,y-) is 25 % of P_{dyn} . But for OP 5, the trend has changed completely and

the two bottom corners are now in comparable overpressure. The sign switch of the pressure dissymmetry coefficient occurring at three corners between planes A4 and A5 for OP3 to OP5 suggest rapid changes in terms of flow dynamics. Because of the complex three-dimensional character of the flow, such variations of the azimuthal pressure distribution are difficult to interpret without detailed information on the velocity field.

3.3. RMS of pressure fluctuations

Figure 5 shows the average of the standard deviations of the four fluctuating pressures measured at a given plane A, normalised by the estimated dynamic pressure at that plane. The normalised fluctuation levels decrease in the first part of the cone in a similar fashion for all operating points. As is confirmed by the spectral analysis of the next section, the dominant phenomenon with fluctuating energy in this part of the cone is the blade wakes and tip vortices which dissipate rapidly inside the cone. Turbulence and other unsteady phenomena are responsible for the increase of the level of pressure fluctuations along the draft tube. Operating points with large flow separation have considerably higher fluctuation levels than points without separation. At the draft tube exit, the pressure fluctuation intensity for OP 5 is more than double than that for the best efficiency point, OP 2. In comparison, differences are small between OP 3 and OP 2.

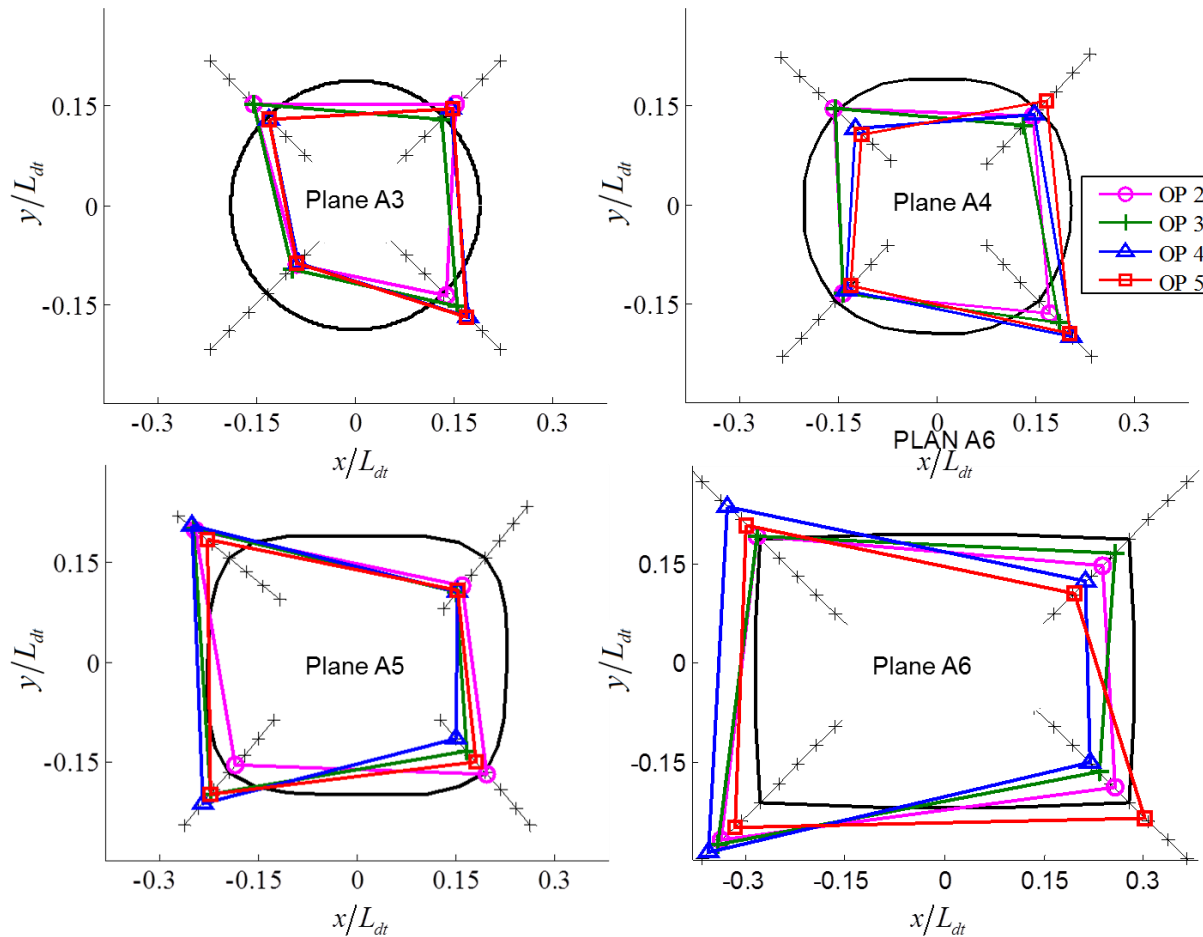


Figure 4. Pressure dissymmetry coefficient $\Delta C_{p_{dissy}}$ for cross-sectional planes A3-A6. The black contours represent the geometrical sections. Diagonal lines are scales of $\Delta C_{p_{dissy}}$ with a graduation corresponding to 0.05. Positive $\Delta C_{p_{dissy}}$ are outside. Lines connecting data points are only for visual aid.

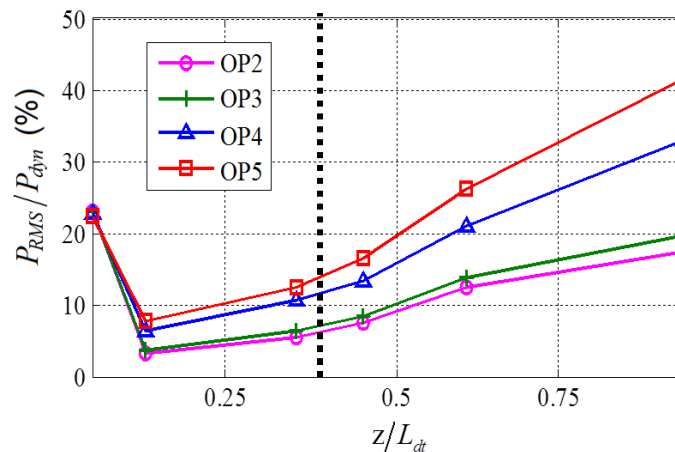


Figure 5. Average pressure fluctuation level normalized by the dynamic pressure for the different planes A and for all operating points. Lines are for visual aid only.

4. Time-dependent wall pressure results

Power spectral densities (PSD) of the instantaneous wall pressure were computed using FFT with 24 samples of 25 000 realisations each. The difference between two frequencies (df) is equal to 0.04 Hz. For the present diffuser, a correlation between separation and a rise in low-frequency pressure fluctuations had already been established [11]. It was found that flow separation is not linked with a single frequency of pressure fluctuations, but with a spectrum of low frequencies up to about $0.5 N$. This is confirmed by figure 6 which shows the ratio between the cumulative PSD for low frequency and the total spectrum. The frequency interval chosen to represent the low frequency content goes from $0.024 N$ to $0.5 N$. The upper limit, $0.5 N$, corresponds to an approximate upper limit of the low frequency bulges of the PSDs that appear due to flow separation. Only the results for the corner (x^+, y^+) are presented in figure 6, but they are representative of those for the other corners in terms of trends. The proportion of low frequency content of the PSDs increases along the diffuser. Operating points with large separation have a much higher proportion of PSD contained in the low frequency range. For OP 5, the energy of pressure fluctuations contained in the chosen frequency interval reaches 85% of the total fluctuation energy at plane A5. At this position, the standard deviation of pressure fluctuations represents 26% of P_{dyn} . The level of wall pressure fluctuations at low frequency, associated to separation, is therefore important.

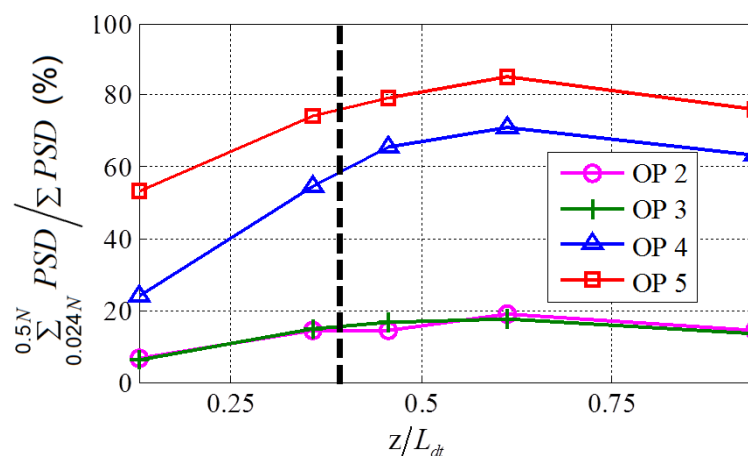


Figure 6. Percentage of PSD in interval $0.024 N$ to $0.5 N$ with respect to total PSD at corner (x^+, y^+) for planes A2 to A6.

Figure 7 presents iso-lines of the PSD with respect to frequency and axial position, for the four corners along the draft tube. In order to establish comparisons that are significant, the spectral densities are normalised by the square of the dynamic pressure and a representative time scale T defined by:

$$T = \sqrt{A} / \left(\frac{Q}{A} \right) \quad (4)$$

where A is the section area at the position of measurement. The frequency is normalised by the runner rotation speed N . Only frequencies higher than $0.024 N$ are represented. The iso-line level chosen corresponds to the approximate cut-off level for the low-frequency bulge of the PSD for OP 2 at A4. OP 2 is selected because it corresponds to the operating point with the smallest separation, and this separation has been visualized at A4. As plotted in figure 7, this chosen iso-line level of the PSDs gives a qualitative representation of the low frequency bulge evolution, but it is by no means an accurate delimiter of such a bulge. The frequencies are represented up to $0.5 N$, to focus on the low frequency range of interest.

For the operating point with small separation, OP 2, the energy bulge at low frequency is negligible. For OP 3, an energy bulge is present at the bottom of the transition section but not inside the conical part. Operating points with important flow separation, OP 4 and 5, have energy bulges extending much further upstream and toward higher frequencies. Pressure fluctuations are always predominant in the bottom of the transition section. But as flow separation expands spatially in the draft tube, the rise in wall pressure fluctuations reaches the conical part and the upper part of the draft tube. These results corroborate the qualitative ones obtained via tuft visualisations [11] in terms of spatial extent of the separated zones and in terms of the observation of complex separation structures with many temporal scales.

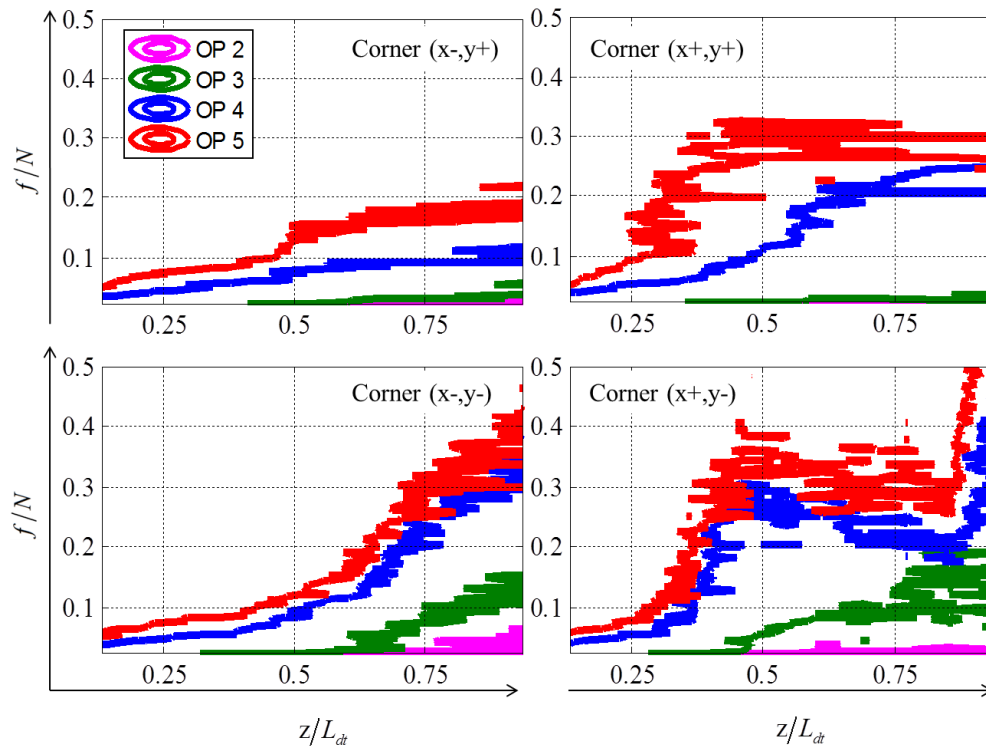


Figure 7. Iso-lines of power spectral density of pressure normalised by the square of P_{dyn} and T . Each sub-figure represents a corner for planes A2 to A6. All iso-lines are at the same normalised PSD value

5. Conclusion

In this paper, the wall pressure inside a bulb turbine draft tube has been investigated using unsteady flush mounted sensors. The draft tube in the present BulbT project is aggressive and generates flow separation in overload conditions. This separation affects the draft tube pressure recovery and so the global efficiency of the turbine. A break off of the efficiency and power curves occurs due to an unsteady flow separation in the draft tube.

In low head turbines, an important part of the total head comes from draft tube pressure recovery. For the analysed operating conditions, more than 85% of pressure recovery takes place in the first part of the draft tube, the conical one. Flow separation starts in the downstream part of the diffuser, in the corner (x+,y-), and extends azimuthally and upstream when opening the guide vanes. The break off of global turbine performance occurs when flow separation reaches the conical part. At locations where separation is present, the pressure recovery decreases significantly and wall pressure fluctuations increase, also importantly. Spectral analysis reveals that the latter increase takes place mostly in the low frequency range up to 0.5 *N* in the form of a low frequency bulge of the power spectral densities. This low frequency bulge expands to higher frequencies as flow separation becomes more important. The full spectrum of frequencies involved in the flow separation process and the convoluted spatial evolution of the mean wall pressure suggest complex and numerous changes in terms of flow dynamics.

This flow dynamics is currently being investigated with the help of various velocity fields obtained through PIV measurements and numerical simulations.

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