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FREQUENCY ANALYSIS OF THE WAKE BEHIND A BAFFLE IN THE PBT MIXING VESSEL

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Abstract

This article is devoted to an experimental investigation of the flow field behind a radial baffles located in a mixing vessel equipped with a pitched blade turbine (PBT) impeller pumping downward. The dynamics of the flow is studied using time-resolved Particle Image Velocimetry (PIV) anemometry method and the various modes are detected using Oscillation Pattern Decomposition (OPD) method. Through OPD analysis, the quasi-periodical structures are revealed and highlighted in the flow structures of the vortex wake. This research explores frequencies which did not exceed blade passage frequency (BPF). Such results can be very helpful to validate CFD models and to design vessels with better efficiency of mixing process.

Keywords: mixing vessel, PBT, PIV, OPD

1 Introduction

Mixing processes are fundamental to a wide range of industrial or chemical applications. The performance of mixing vessels significantly impacts product quality, process efficiency, and energy consumption. Among the various types of mixing impellers, the Pitched Blade Turbine (PBT) is widely used for its versatility and effectiveness in handling diverse mixing tasks, covering all phases of substances.

The PBT impeller features blades set at an angle, typically between 45° and 60°, which enable it to generate both radial and axial flow components. This dual-flow capability makes PBTs particularly suitable for achieving effective mixing process in vessels for substances with different physical properties.

Despite their widespread use, optimizing the performance of PBT-driven mixing vessels remains a challenge. Mixing process in a standard vessel driven by the impeller is well described in classical book of mixing [1]. Factors such as liquid level, impeller size, blade angle, rotational speed, and the geometry of the mixing vessel significantly influence the flow macro-instabilities (MI) and other large-scale flow structures responsible for mixing quality. The impeller discharge jet (IDJ) affects the region below impeller while the impeller sucking jet (ISJ) contributes to the disintegration of macro structures and mainly affects vertical flow near the baffles typically resulting in macro-swelling (MS) of the surface. The most dominant structure is primary circulation loop (PCL) induced by IDJ. This structure exhibit quasi-periodical behaviour; each cycle can be divided into four phases: generation, expansion, oscillation and disintegration [2].

When MI dominates in the flow field, there are typical frequency values substantially lower than other flow characteristics such as BPF or frequencies in the vortex wake behind baffle where Kelvin-Helmholtz instabilities might be expected.

The literature review covers mainly mathematical studies, e.g. [3] as well as experimental one, very typically based on using PIV measurement [4]. There are also comparative studied relying on LDA anemometry and CFD turbulence modelling [5, 6]. The structure of PCL was described in our previous research [2] when the emphasis was on the vertical plane of measurement. The investigation in horizontal planes is not so typical. And more, the effect of baffles is very often not taken into account in detail. That is why further exploration is required to address the complexities as the vortex wakes behind baffles.

Therefore, the aim of this article is to experimentally investigate the frequency characteristics of the structures occurring in the baffle region in various horizontal planes and to help clarify their effect.

2 Experimental setup

There is a schematic design of the mixing vessel in figure 1. A tank with circular cross section has diameter T equal to 240 mm and this value corresponds to liquid level height H. The tank is stirred by PBT impeller with six blades, each inclined by 45°, outer diameter (D = 0,4T) is 96 mm. The baffle width b is 0,1T. The impeller is pumping the liquid downwards and its off-bottom clearance is C = D. The coordinate system origin was located at the center of the bottom wall. This paper presents only horizontal planes of measurement (PoM) with coordinates x-y. More details can be found in [2].
The horizontal planes location is reported for non-dimensional coordinates

$$z' = \frac{2z}{C} \quad (1)$$

The tested planes were situated at z = 25, 58, 70, 90 mm below the impeller and 160 and 215 mm above. This corresponds to z'=0.52, 1.21, 1.46, 1.88 below and 3.33 and 4.48 above for no-dimensional form. Three distinct impeller revolutions were tested: N_{imp} = 150, 400 and 600 rpm, or 2.5, 6.67 and 10 sec^{-1}. The blade passage frequency is then 15, 40 and 60Hz and tip velocity 0.75, 2 and 3 ms^{-1}, respectively.

Time-resolved PIV is effective technique to study the flow structures during mixing process. It can capture flow structure with sufficient time and space resolution to analyze macro-instabilities and other high- and low-frequency structures in the tank. The most important part of this anemometry system is a laser and a camera. Laser New Wave Pegasus Nd:YLF has double head, wavelength is 527 nm, maximal frequency is 10 kHz, a shot energy is 10 mJ for 1 kHz. Camera Phantom V611 has maximal resolution 1280 x 800 pixels, which correspond to maximal frequency 3000 double-snaps per second. The internal memory of this CMOS camera is 8 GB. The hollow glass particles coated by silver were used for seeding.
To compare with other authors, it is desired to recalculate detected frequencies to non-dimensional form

$$F' = \frac{f}{N_{imp}} \quad (2)$$

and concerning the number of used blade N_B

$$F'_{BPF} = \frac{F'}{N_B}. \quad (3)$$

On the other hand, coordinates in horizontal PoM (x, y) remained in their dimensional form as well as the velocity components u and v (and velocity magnitude L).

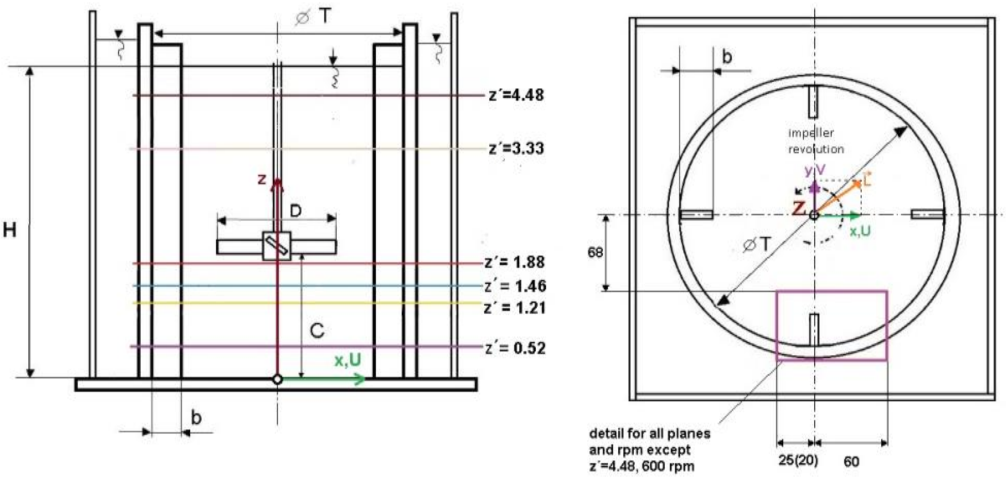
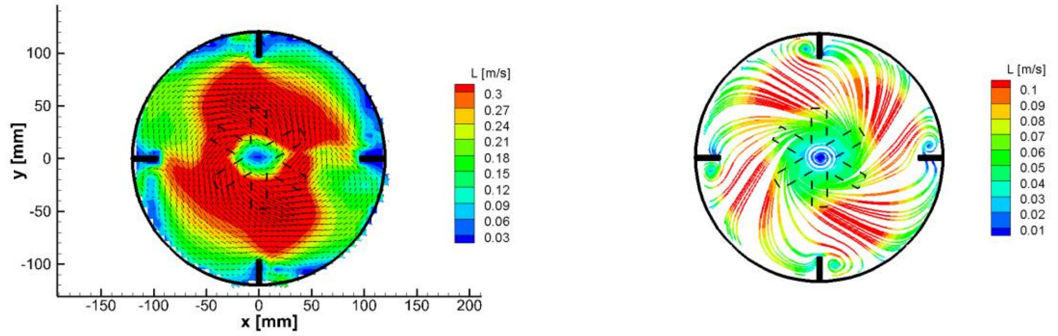


Figure 1: Side view and top view of the mixing vessel including PBT impeller and depicted horizontal planes of measurement.

3 Results and discussion

The acquired raw data was taken using DynamicStudio from Dantec company and further analyzed using Matlab and Tecplot software. The black vectors represent the mean flow field velocity vector calculated from both components in PoM, the color represents the distribution of scalar value (either the velocity magnitude L or the intensity of fluctuation – sum of velocity variation). Fast Fourier transform (FFT) reveal spectrum (periodogram) which is calculated at one distinct point of PoM.

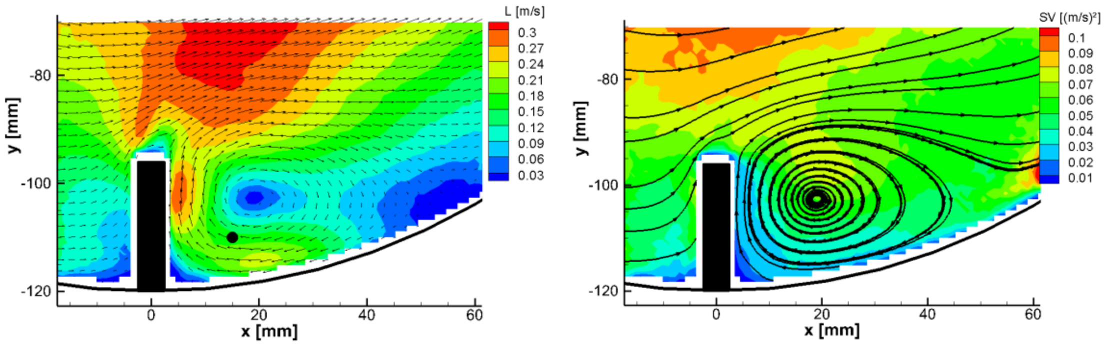


(a) (b)

Figure 2: (a) The distribution of mean velocity L at plane z = 70 mm and (b) z = 25 mm, both for 400 rpm. Velocity vector (a) and vector lines (b) reveal the flow topology.

The mean flow field (unlike instantaneous values) is more or less symmetrical (see figure 2) along two lines perpendicular to each other and rotated by 45° relative to the coordinate system. In the region just below the impeller, there is significant axial velocity component (which cannot be detected from horizontal PoM) as well as radial component (red color in figure 2a) for distance z = 70 mm. There can be seen velocity deficit in front of the baffles (related to counter-clockwise motion of the impeller) and the wake occupied by steady vortex. Similar flow patter is visible in figure 2b where colored vector lines are used to fully reveal the flow pattern. This result was taken for z = 25 mm, so closer to the bottom of the vessel. Notice, the maximal radial flow component is located further from the impeller axis there.

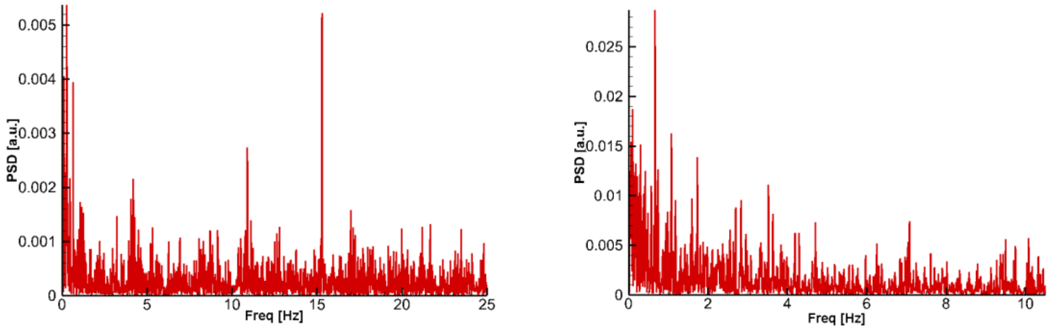
Since the main task of this paper is frequency analysis, the mean flow field was present here only for two typical planes within IDJ. This is incidentally the region where the highest frequency value can be detected. It is BPF which is just below the impeller blade (z = 90 mm) and the spectrum is plotted in figure 4a with peak frequency at 15 Hz. Frequencies of macro-instabilities as PCL or FMF (flow macro-formation) are much smaller (in the order of tenths of Hz) and peak frequency values in order of units occurs in the wake behind baffles.



(a) (b)

Figure 3: The wake (steady vortex) behind one baffle. The distribution of mean velocity L (a) and the plot of fluctuation activity using sum of velocity variances (b) were used.

Further in the text, only one regime under N_{imp} = 400 rpm and at z = 70 mm will be presented in detail. The figure 3 is plotted to show the wake (the right side from the baffle) in mean flow field values. The center of steady vortex is created by velocity deficit, on the other hand, the velocity overshoot can be seen in close proximity of the baffle as dark red color. The vector lines reveal the steady elongated vortex (Fig. 3b) with dimensions exceeding the baffle width. The frequency spectrum of point X [15;-110] mm, which can be seen as the black spot in figure 3a, is plotted in figure 4b. The main frequency peak at 0.68 Hz corresponds to OPD mode No. 4 as its associated frequency is 0.65 Hz (see table 1).



(a) (b)

Figure 4: (a) Frequency spectrum just under the impeller blade (z = 90 mm) to detect blade passage frequency equal to 15 Hz. (b) Frequency spectrum at point near the baffle in plane z = 70 mm.

OPD decomposition is similar to dynamic mode decomposition methods. Every mode is characterized by constant frequency value associated with the topos, e-folding time and periodicity. Each topos is complex and is composed from real and imaginary part. The real part has phase angle equal to zero while imaginary part has phase angle 90°. Topos can be animated to visualize features such as traveling vortices in the flow. More information can be found in [2]. There is table with five OPD modes with most significant periodicity. The frequency of mode No. 4 is very similar to frequency peak and probably represent similar flow feature. There are other four different modes. The very first one is associated with high frequency (5.3 Hz), nevertheless its e-folding time is rather short. The bigger e-folding time, the smaller damping and the longer lasting process. The third one represents the periodical shedding of vortices (analogy to K-H instability). The most stable (concerning e-folding time) is just the mode No. 4.

Table 1: The most important OPD modes concerning periodicity in plane z = 70 mm for 400 rpm.

mode	Frequency [Hz]	e-folding [s]	Periodicity
1	5.3048	45.711E-3	242.49E-3
2	3.7672	63.636E-3	239.73E-3
3	1.9899	86.596E-3	172.32E-3
4	646.78E-3	151.12E-3	97.740E-3
5	468.09E-3	77.749E-3	36.393E-3
6	0	169.90E-3	0
7	0	46.545E-3	0
8	0	54.504E-3	0

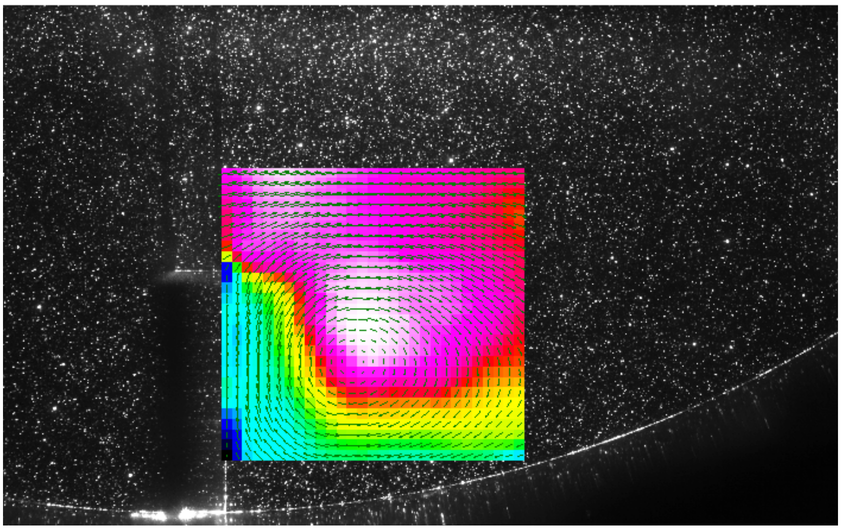


Figure 5: The raw image from PIV measurement – white points represent the seeding particles. The evaluated region for OPD decomposition is situated just behind the baffle.

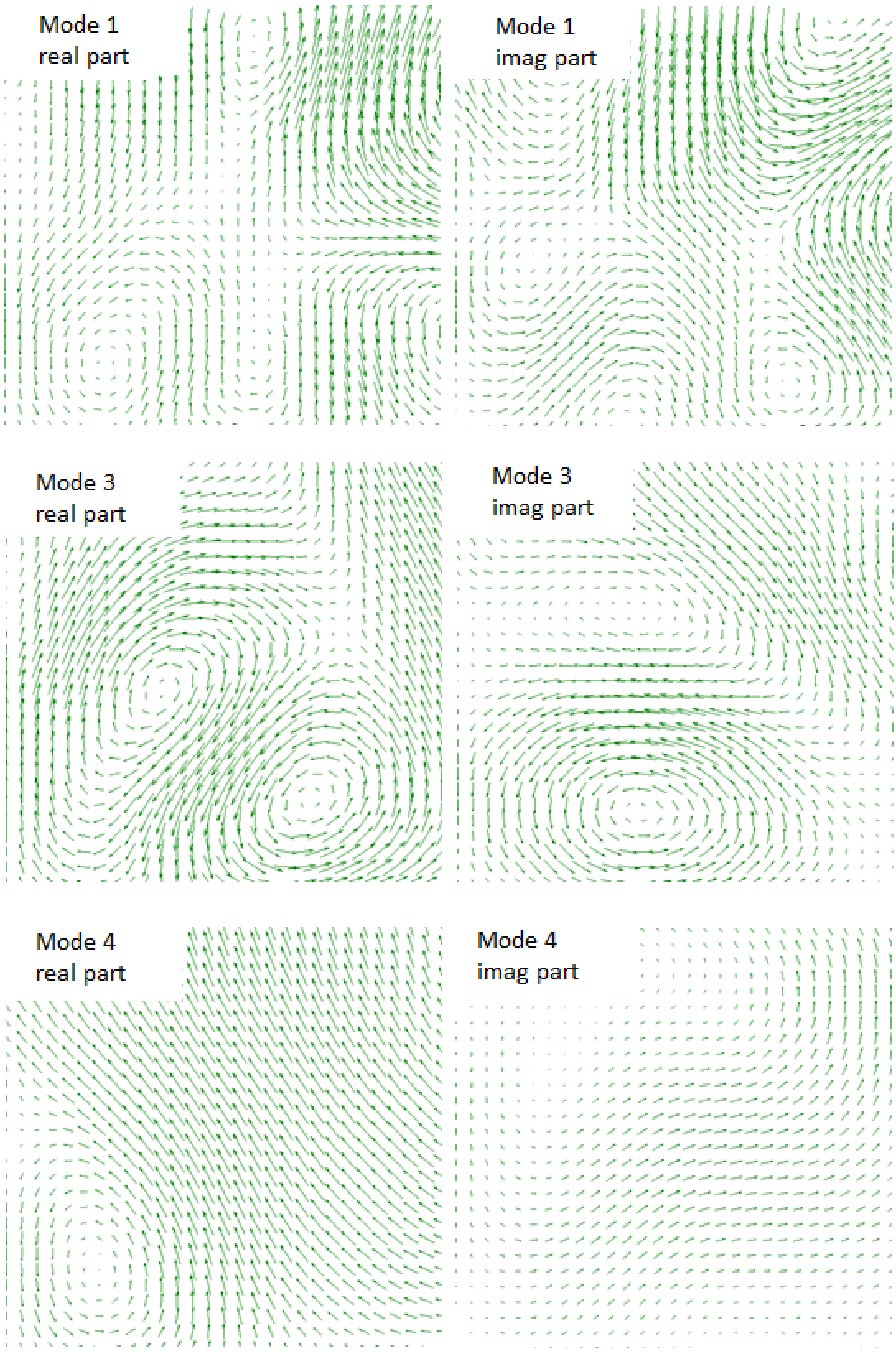


Figure 6: Real (left column) and imaginary (right column) part of OPD topos for modes No. 1, 3 and 4.

4 Conclusion

The experimental investigation of the flow field in the vicinity of the baffle inside the mixing vessel driven by PBT impeller was studied. The advanced optical anemometry TR-PIV was applied as it enables to provide spatiotemporal correlation as it has high resolution in space and time. There were detected high frequency values that are related with the impeller discharge jet (IDJ) and mainly much lower values connecting with macro-instabilities. Their values are typically up to 0.15 [-] in non-dimensional form and are related to oscillation of primary circulation loop (PCL) and the disintegration of the flow near the baffles.

Continuing research on PBT mixing vessels is essential due to their critical role in numerous industrial processes. Optimizing mixing performance can lead to significant improvements in process reliability and energy efficiency. Different vessel - impeller configurations are required to meet the diverse demands of applications, e. g. the mixing of multiphase substances or non-Newtonian fluids. To understand the fluid dynamics in mixing vessels is crucial because it enables better scale-up from laboratory conditions to industrial applications. Additionally, improvements in computational and experimental modelling can uncover innovative designs or working cycles which can help with the biggest industrial challenges of recent times such as environmental sustainability and carbon neutrality goals.

Presented acquired experimental data have shown the ability of PIV system to gain the data in any planes or points regardless of whether they are oriented vertically or horizontally. The ability to measure very close to a curved surface was also presented. Such a detailed dataset can be used to validate mathematical models which will certainly be used in near future for further improvements of mixing vessels properties.

Acknowledgement

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