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RESEARCH ARTICLE

Commencement and Development Processes of Flow Unsteadiness at Tip Clearance Region of a Low Speed Axial Compressor Rotor Blade Row

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Abstract
Commencement and development processes of unsteadiness, caused by blade row tip leakage flow in a low speed axial compressor, are investigated and results are presented in this paper. Analyses are based on results obtained through numerical simulation of unsteady three dimensional viscous flows. Discretization of the Navier-Stokes's equations has been carried out based on upwind second-order scheme and k-ω-SST turbulence modeling was used for estimation of eddy viscosity. Three different circumstances, including design point and two near stall conditions are considered for investigation and discussion. Tip leakage flow frequency spectrums were examined through surveying instantaneous static pressure signals imposed on the blades surfaces. Focusing on time dependent flow structure results signified existence of some pressure peaks at near stall conditions. These regions, which are created as a result of interaction between main inflow and tip leakage flow, lead to occurrence of self-induced unsteadiness. However, at design condition, flow is more affected by the main inflow instead of the tip leakage flow. By occurrence of self-induced unsteadiness, which occurs at near stall condition, tip leakage vortex flow starts to fluctuate at a frequency about the blade passing frequency. Further decrease in the flow rate up to a specified value showed no significant variations in the leakage flow frequency, but, on the other hand, magnified amplitudes of this unsteadiness.

Keywords
axial compressor, flow structure, self-induced unsteadiness, tip leakage flow

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1 Introduction

Unsteady flow on tip clearance region are one of the originating source of noise, blade vibration, losses, decrease of efficiency and disturb of flow structure inside compressor [1].

To optimize aerodynamic design, achievement of higher performance and avoidance of instability, evaluation of relation between tip leakage flow and other flow phenomena is essential. With significant development of numerical methods and computational power, computational fluid dynamics is a proper tool to study complex flows.

Different studies about relation between tip leakage flow and stall inception was accomplished [2-3]. In this respect, two criteria in occurrence of spike stall in high speed and low speed axial compressor are proposed [4-5].

While the tip leakage flow has been under prevalent studies for many years, its unsteadiness is a new focus in axial compressor research.

One type of unsteadiness in axial compressor is rotating instability. Mailich et al. reported the phenomenon in one operating condition, tip leakage vortex moves from one blade to another. This phenomenon is studied at both low and high speed compressors [6]. Marz et al ascribe this phenomenon to existence of induced vortex that rotated about 50% blade passing frequency [7]. Hah et al. surveyed the occurrence of this phenomenon at high speed compressor experimentally and numerically, respectively [8]. They show the unsteadiness originated from interaction of induced and shock vortex.

Furukawa et al. numerically represented Consequence of tip leakage vortex breakdown [9-10]. It is indicated that tip leakage vortex breakdown result in unsteadiness in compressors. Also, Yamada et al. recognized this kind of unsteadiness in transonic axial compressor [11].

Other type of unsteadiness that happens at high loading operating condition in tip leakage region is self-induced unsteadiness. In this respect, Graf find out the periodic oscillations of tip leakage flow [12].

Zhang et al. numerically reported formation of self-induced unsteadiness at low speed axial compressor [13]. They observed interaction of incoming main inflow and tip leakage flow leads to the same kind of unsteadiness. At other study, existence of this event is shown at high speed axial compressor [14]. Moreover originating mechanism at transonic axial compressor is compared to low speed axial compressor.

At above studies, flow analysis is performed at just operating condition in which self-induced unsteadiness occurred. In order to achieve to deeper understand about permanence of self-induced unsteadiness and its effects, flow analysis at lower mass flow rates are required. Thus, in this paper, via unsteady analysis at different operating conditions from design point to near stall conditions, self-induced unsteadiness process is evaluated. This kind of unsteadiness occurs at Specific mass flow rate. Originating mechanism and its flow frequencies are assessed. Limit of mass flow rate in which self-induced unsteadiness occurs is also identified. In this limit, no phenomena happen except self-induced unsteadiness. Flow structure, its frequencies and amplitudes are compared accurately. Also the required number of passage for capturing this phenomenon is recognized.

2 Model specifications and numerical model

A low speed isolated axial compressor rotor blade row has been considered as the case study in the present research work. This blade row has already been used by some researchers to study its flow field structure from numerical or experimental point of views. There are also some research works which are focused on blade tip leakage flow structure of this compressor [15]. This blade row comprises 12 blades with 117.5 mm in its tip chord size and a tip clearance of 2mm. Test Reynolds number based on the blade midspan chord length and rotational speed of the rotor blade row are 3.77×10^5 ,1300 rpm, respectively.

As is shown in Fig. 1, four blades have been used for the numerical simulation purposes. Appearance of a small flow disturbance at the rotor tip in 2-3 blade pitch. On this basis, Different studies illustrated that four blades are sufficient for investigating this phenomena. So, four blades have been used for the numerical simulation purposes. This number of blades guarantees to capture the flow unsteadiness. Since only a part of full passages were calculated, considering the extreme boundaries along the circumferential direction as the repeating areas could be of a reasonable decision. A multi-block structured grid has been employed for the mesh generation. Each passage consists of 74 streamwise nodes, 50 spanwise nodes and 60 nodes along the pitch direction. The distance between the blade tip and the casing wall was divided into 16 nodes to assess the tip leakage flow correctly. Fig. 1 shows the surface grid system generated on solid walls of the model. Grid density near to the walls was set somehow to provide $y^+<5$. So, it would be possible to assess viscosity flux close to the walls without using any wall function and only by considering no-slip condition and adiabatic wall. The whole grid structure at four passage consisted of about 1170000 cells.

In the present investigation a commercial flow solver package of Fluent was used for simulations of three-dimensional, viscous and unsteady flow. The computation method utilizes a finite volume scheme for solution of governing equations of continuity and momentum. Coupling of velocity and pressure fields was carried out by the usual simple algorithm. Second order implicit scheme has been applied for time discretization. To estimate the eddy viscosity, the k-ω-SST turbulence model was employed.

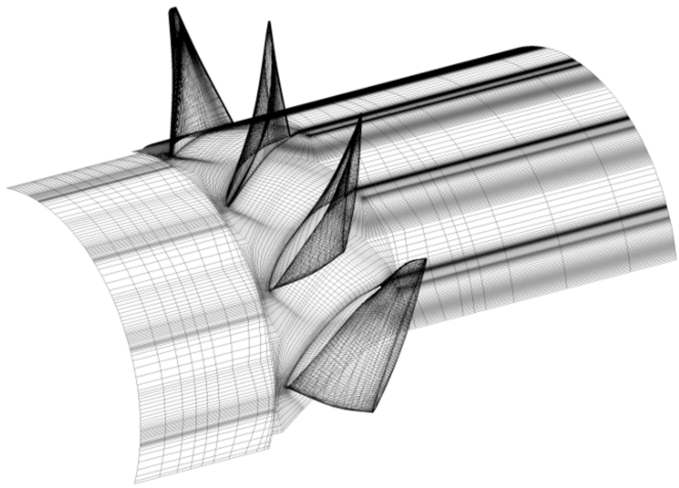

Fig. 1 Computational grid structure on the blades and hub solid walls

As the boundary conditions, inflow velocity and its direction were imposed at the rotor blade row entrance. For the outlet boundary, static pressure was distributed along the blade span by means of the well-known radial equilibrium law. No-slip and adiabatic conditions were imposed on all the solid walls. Periodic boundary conditions were imposed over the farthest boundaries in the circumferential direction.

In the unsteady simulation process, the time step was chosen in such a way that one blade passing to be completed in 120 steps. This in turn, corresponded to 1440 time steps for completion of one full rotor revolution. Since the angular velocity of the rotor was 1300 rpm, one revolution was completed in 4.6×10^{-2} sec. As a result, a time step of 3.2×10^{-5} sec was used in the present study. As a result, adopted sampling frequency is about 31 KHZ while blade passing frequency is 260 HZ. The CFL number varied between 1 and 4. In the present work, twenty inner iterations were performed at each time step.

The residual values of the main governing equations approaching to around 10^{-7} were used as the convergence criteria in numerical simulation process. As the complementary convergence criteria, statistical steady state monitoring of the flow variables at some selected points were also carried out.

3 Results and Discussion

3.1 Numerical scheme validation

The low speed isolated axial compressor rotor blade row has been chosen as a test model. This compressor has been utilized for numerical and experimental studies about tip leakage flows and effects [15].

3.2 Tip leakage flow unsteady results

Results of unsteady analyses of the tip leakage flow of the test model from design point to near stall conditions are presented in this section. These conditions are introduced by different flow coefficients of φ= 0.5, 0.38 and 0.36. The first flow rate belongs to the design condition and the two other refer to conditions close to the stall point (see Fig. 2).

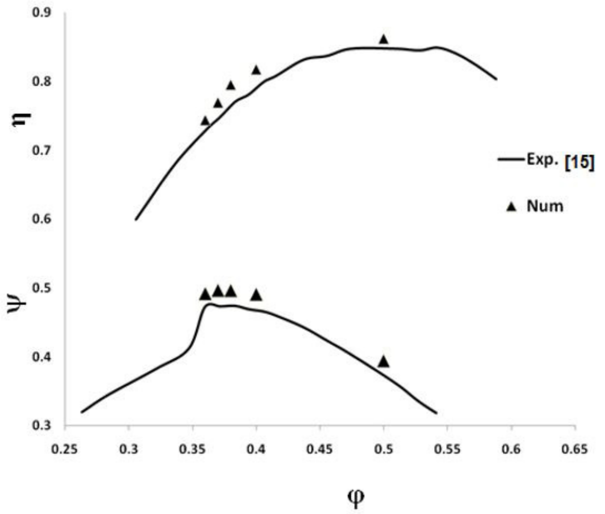

Fig. 2 Compressor blade row performance map

Relative total pressure coefficient (C_{rpt}) results are presented in Fig. 3 at different instances. Streamlines patters are also superimposed on these figures at T=0. The interface between the main flow and the tip leakage flow can be observed clearly. The region of nearly constant Crpt belongs to the main inflow (the region of red color). In other words, the region prior to this interface belongs to the main stream and after that to the tip leakage flow.

As can be detected from Fig. 3, in design condition (i.e., φ= 0.5), due to the low strength of the tip leakage flow in comparison to the main inflow, a small region of the passage is affected by the tip flow. Consequently, resultant flow at the tip region would be steady. By approaching to the stall flow rate (i.e., φ=0.38 and 0.36), tip leakage flow gets its dominant effects, and as a result, cause the main inflow to be blocked and turn towards the pressure side of the adjacent blade.

Interaction of the main inflow and the tip leakage flow cause the stagnation point to occur prior to the interface. This high pressure point pushes the low pressure regions back the interface. Subsequently, due to this pressure difference, flow starts to fluctuate. These fluctuations in the flow field are referred to the self induced unsteadiness. For a better recognition of this phenomenon high pressure and low pressure regions are designated by symbols H and L, respectively, in Fig. 3. Region H pushes region L, which is the main reason for self induced unsteadiness. Moreover, impingement of the tip leakage flow to the pressure side of the adjacent blade causes further unsteadiness. For the test model the self induced unsteadiness appeared first at φ=0.38. Flow structure is similar for all passages at this flow rate. This flow similarity continues for lower flow coefficients up to φ=0.36. At lower φ values, flow structure does not remain similar in the passages and signs of stall inception can be observed within the flow passage. These latter results are not presented here, since they are beyond the scope of this paper.

Experimental results of Inoue et al. [15] denote that the centerlines of the tip vortices are accompanied by minimum pressure regions. So, by tracking on the pressure fields, the position of tip leakage vortex and its trajectory could be distinguished.

Static pressure fields for all operating conditions are shown in Fig. 4 for 97% blade row span. Results include five successive moments with a time interval of T/4.

At φ=0.5, the main inflow passes from the passage without development of significant tip leakage vortex flow, therefore the flow field would be steady. At φ=0.38 and 0.36, existence of low pressure spots can be observed within the flow field, which are introduced by dashed line circles (see Fig. 4). Streamlines pattern shows that the interaction between the tip leakage flow and the main inflow results in development of the tip leakage vortex flow. In the two operating conditions of φ=0.38 and 0.36 the process of generation to dissipation of the tip leakage vortex occurs within the time period of T. So the tip leakage vortex has a periodic behavior with a frequency of about the blade passing frequency.

The tip leakage flow at φ=0.36 is stronger than that for φ=0.38. As a result, the generated vortex flow at the mid region of the blade passage moves towards the leading edge of the adjacent blade and then moves downstream. At φ=0.38, tip leakage vortex forms close to the blade pressure surface. This region moves downstream and then dissipates at about T (follow the results for the successive times starting from T=0 in Fig. 4).

Comparing the results of φ=0.38 with those of φ=0.36, one can realize that the region in which the vortex core starts to form and also its trajectory are different at these two flow rates.

The root mean square (RMS) values of the static pressure coefficients can be employed to quantify the unsteady behavior of the tip leakage flow including its intensity, trajectory and size. These results are shown in Fig. 5 for a stream surface of 97% blade row span. At φ=0.5 no evidence of tip leakage vortex, including its trajectory and fluctuation, can be observed. However at φ=0.38 and 0.36, the unsteady pressure fluctuations originate from the blade leading edge and move towards the pressure side of the adjacent blade along the dotted line. In other words, the tip vortex fluctuates around this line. Reducing mass flow rate from φ=0.38 to 0.36 results in augmentation of fluctuations intensities.

Fig. 6 illustrates RMS values of the static pressure coefficient at six axial positions of 0%, 20%, 40%, 60%, 80% and 100% of the blade chord length, measured from its leading edge in all operating conditions. Focusing of the results presented in this figure and Fig. 5 one can realize that at φ=0.38 the maximum fluctuations of static pressures occur around 40% of the axial chord length.

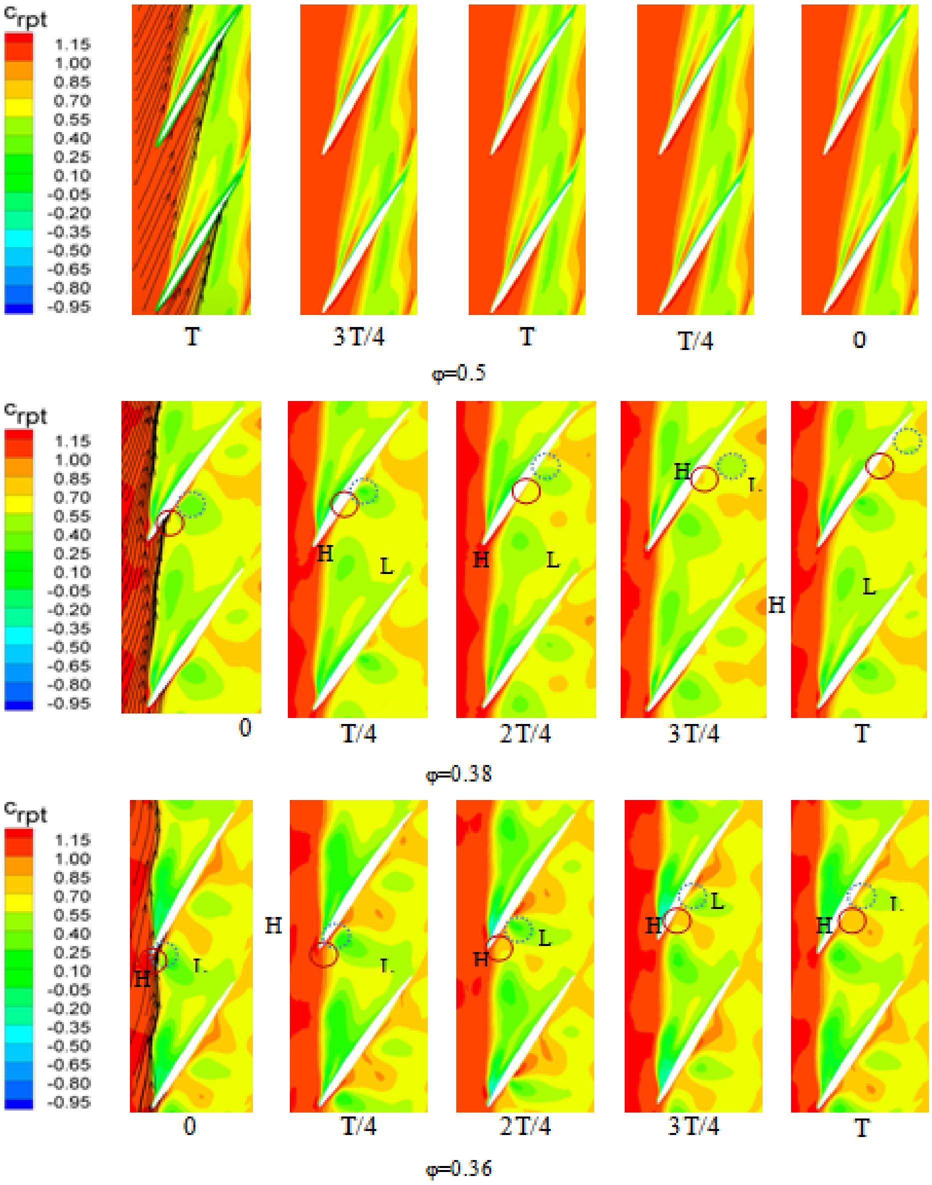

Fig. 3 Unsteady fluctuations of static pressures on 97% span stream-surface

By reducing the mass flow rate, this position moves towards the blade leading edge at about 20% of the axial chord length.

3.3 Frequency analyses

Unsteady nature of the tip leakage flow can be investigated through surveying the instantaneous surface pressure signals. In this respect, seven pseudo pressure transducers were distributed along the pressure side of the blade at the same span close to the blade tip. These transducers were located at 10% to 90% of the chord length measured from the blade leading edge. Static pressure signals were picked up after the final convergence of the numerical calculations at each instant. Fig. 7 shows raw signals of the static pressures and FFT analysis for P1-P7 points at the all operating conditions.

It can be realized that at the design condition (i.e., φ=0.5), amplitudes of oscillations are very low. This shows the weakness of the tip leakage flow relative to the main inflow. Results obtained at the near stall conditions (i.e., φ=0.38 and 0.36) illustrated that the dominant frequency for all the monitored points is about 1.1 BPF. Since the test points are imposed on the blades solid surfaces and rotate with them, the blade passing frequency should not appear in the FFT results. Consequently, this frequency would be the tip leakage vortex frequency. This matches with the results presented in Fig. 4, where the time interval between the vortex generation to its dissipation was about T. Reduction of the mass flow rate from φ=0.38 to 0.36 leads to an increase in the amplitude of the oscillations without development of any lower frequencies. In other words, the self induced unsteadiness, which is created at φ=0.38, continues to occur at φ=0.36 but with a higher intensity. It can be detected from Fig. 7 that reduction of the flow coefficient from φ=0.38 to 0.36 leads to the shift of the position of the maximum amplitude of the fluctuations (i.e., from point p5 to p1). This result is consistent with the result obtained from Fig. 5.

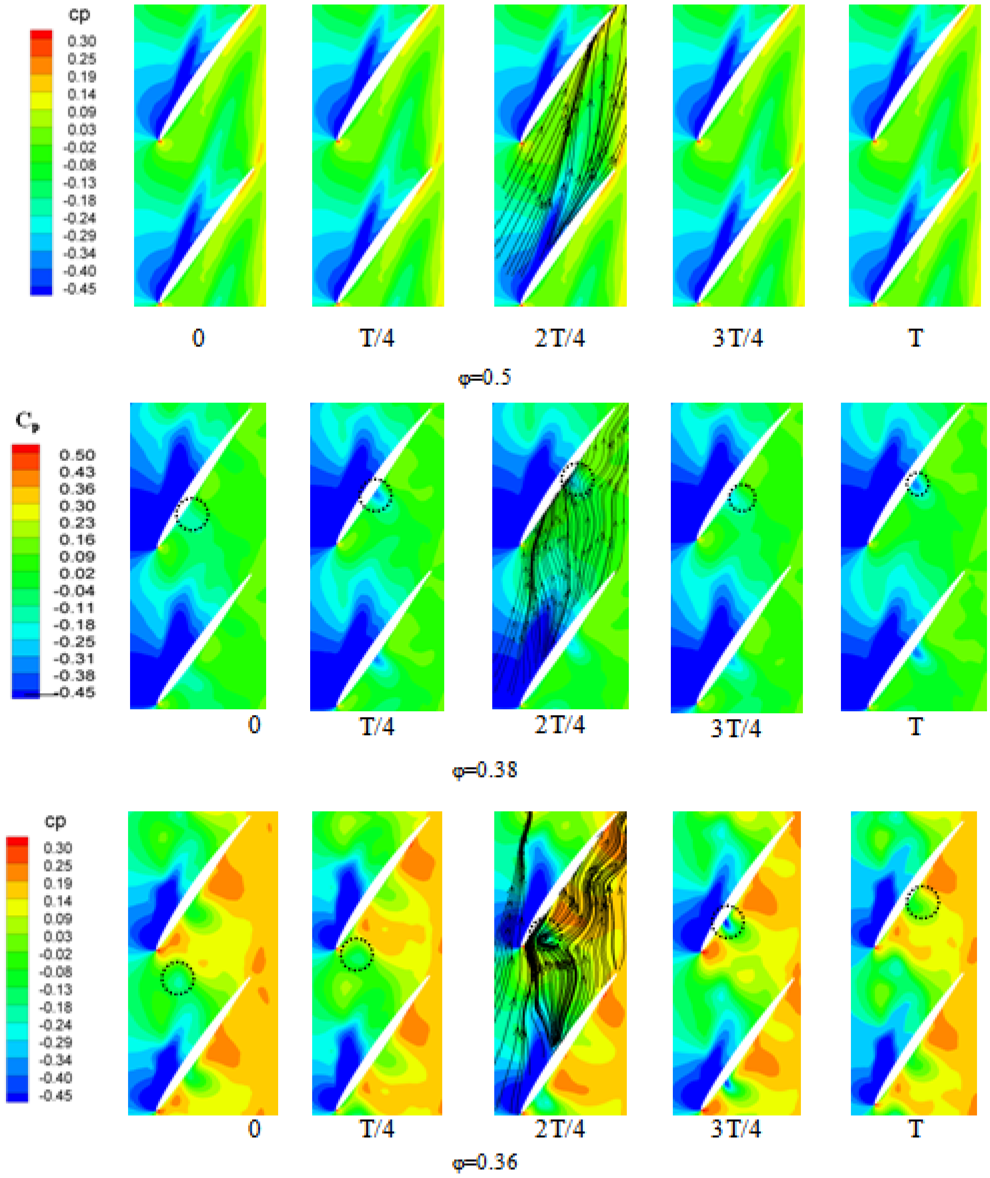

Fig. 4 Unsteady fluctuations of static pressures on 97% span stream-surface

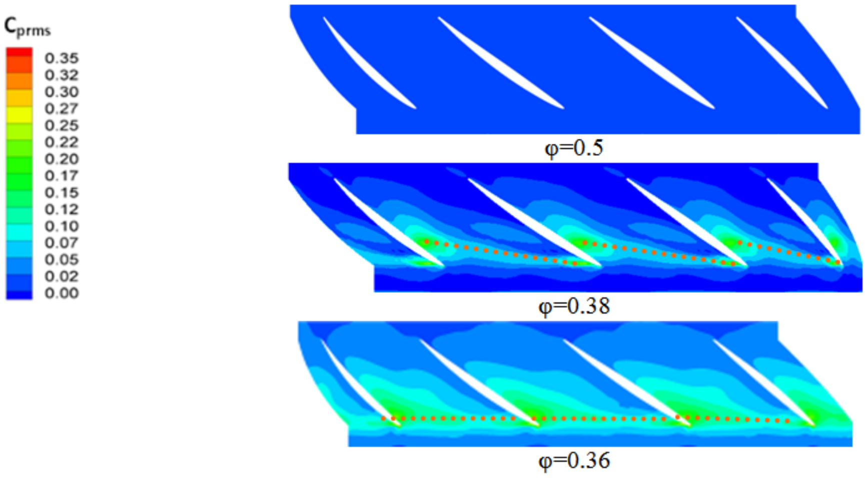

Fig. 5 Unsteady fluctuations of static pressures on 97% span stream-surface: a) φ=0.5, b) φ=0.38, and c) φ=0.36

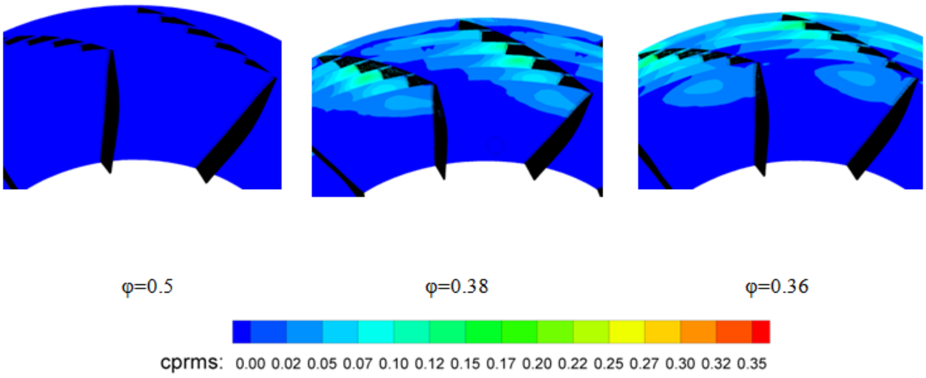

Fig. 6 Unsteady fluctuations of static pressure coefficient at different axial positions: a) φ=0.5, b) φ=0.38, and c) φ=0.36

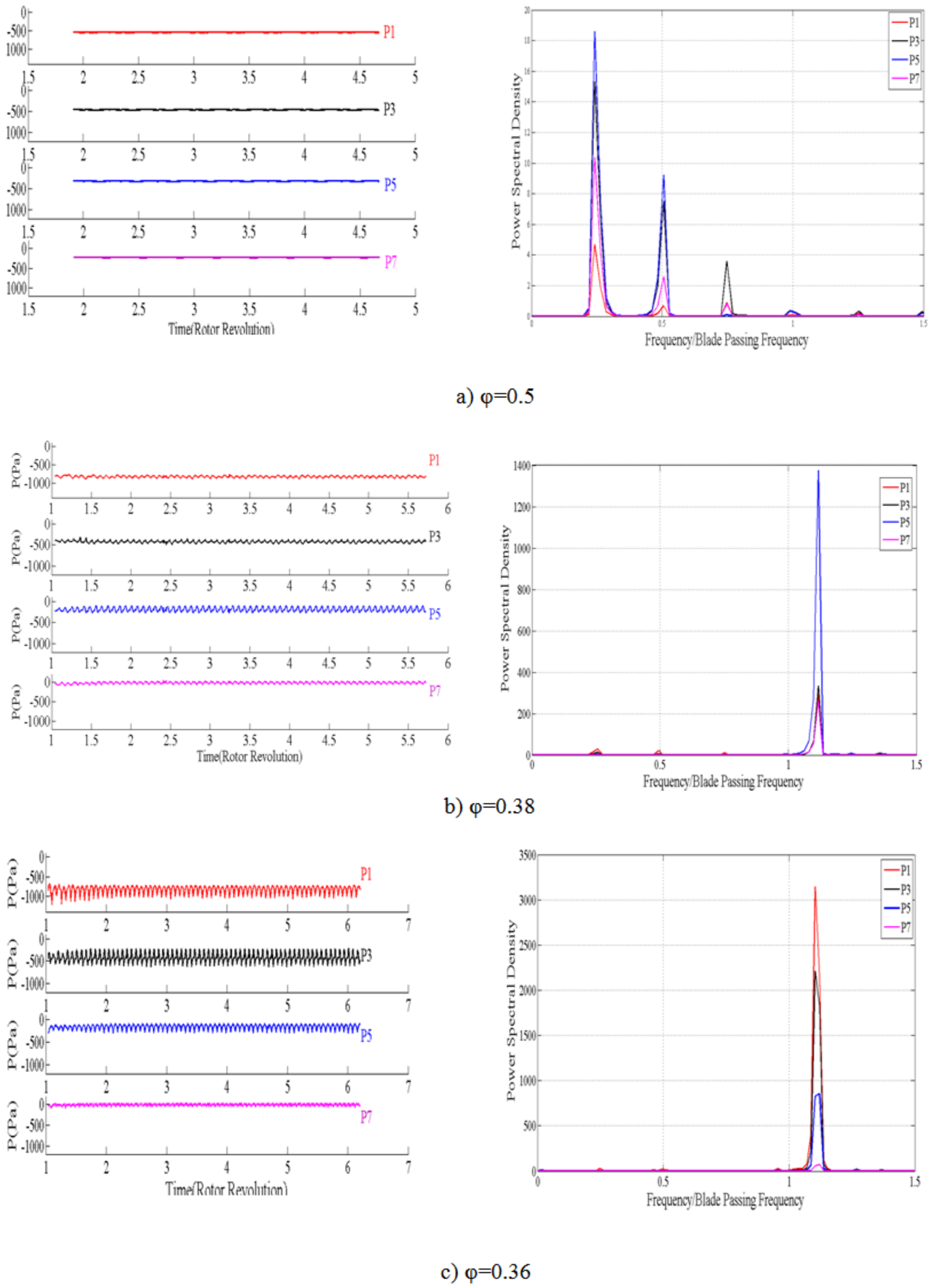

Fig. 7 Raw signals of instantaneous surface static pressures and their frequency spectrums at different axial positions

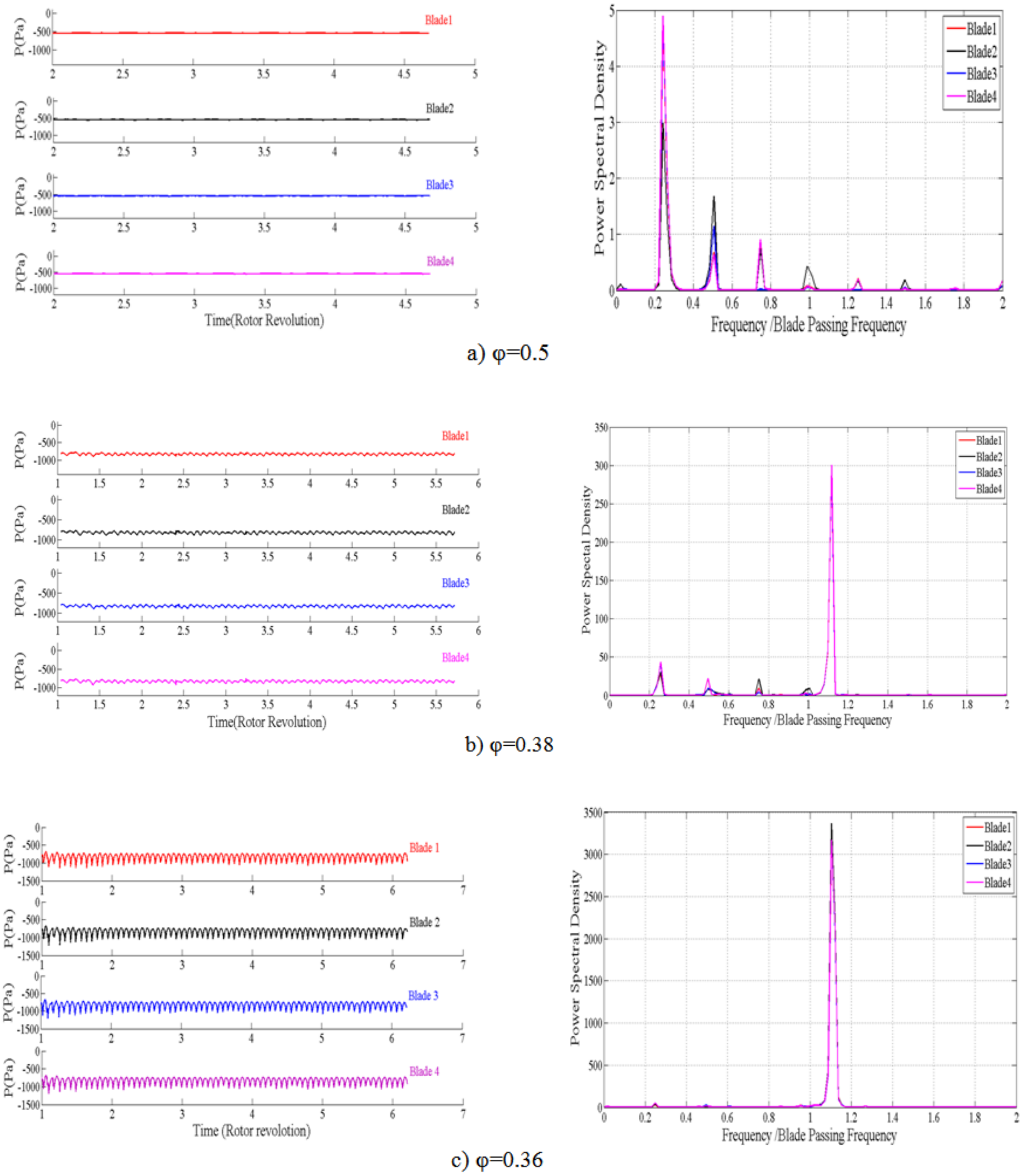

Fig. 8 Raw signals of instantaneous surface static pressures and their frequency spectrums at 10% chord of each blade

Frequency spectrum results at point P1 (10% chord) of each blade is shown in Fig. 8. The same frequency and amplitude can be observed for φ=0.38 and 0.36 cases for all of the blades. So, even after occurring the self induced unsteadiness, there would not be created any peripheral disturbances.

4 Conclusion

The main purpose of this research work is to study the process of origination and development of self-induced unsteadiness caused by tip leakage flow in a low speed axial compressor. Numerical analysis of unsteady tip leakage flow was carried out for three different mass flow rates from design point to close to stall conditions. Main results drawn from this study are summarized as the following.

Reduction of flow coefficient from design point (i.e., φ=0.5) to specific mass flow rate (i.e., φ=0.38), led to occurrence of self-induced unsteadiness.

In mass flow rates corresponding to self-induced unsteadiness, frequency of oscillation tip leakage flow is about blade passing frequency. In addition, this frequency at all monitored points distributed along blade chord is identical.

As mass flow rate reduces from φ=0.38 to 0.36, self induced unsteadiness continues to occur with higher amplitude without formation of any new dominant frequency. In addition, at this range of flow rate, all passages experience a similar flow structure.

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