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Experimental investigation of unsteady flow in a vertical shaft axial flow pump

Düşey milli eksenel bir pompada zamana bağlı akışın deneysel olarak incelenmesi

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Experimental Investigation of Unsteady Flow in a Vertical Shaft Axial Flow Pump

Highlights

- *The effect of unsteady flow inside the pumps on pump performance characteristics.*
- *Instability problem in pumps due to rotor-stator interaction and recirculation.*
- *Measurement of unsteady flow inside the pump with piezoelectric pressure transducers and determination of flow-induced vibrations.*

Graphical Abstract

Unsteady flow inside a vertical shaft axial flow pump is measured with a piezoelectric pressure transducer and spectrums are obtained. Spectrums are compared with the vibration data.

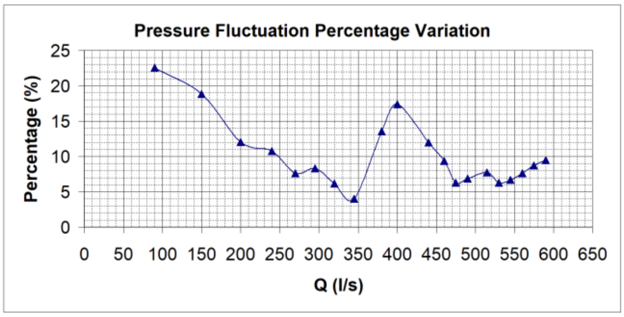

Figure. Pressure Fluctuation Percentage Variation at Different Flowrates

Aim

It is tried to determine the recirculation structure and contribute to the literature on this subject by examining the flow structure with laboratory experiments at different operating points for the pumps. It is aimed to get a test method to obtain the instability characteristics of the pumps.

Design & Methodology

The pump is designed and manufactured. Laboratory tests of the pump are performed in the designed experimental setup.

Originality

Measurements are made with a waterproof piezoelectric pressure transducer in a vertical turbine axial flow pump. Investigation of unsteady flow and flow-induced vibration by using accelerometers.

Findings

Performance characteristics of the pump is determined experimentally and the region of instability in the pump performance characteristic also found by measuring the pressure fluctuations and vibration spectrums. The onset of recirculation is found from the measurements.

Conclusion

According to the results obtained, it is possible to make improvements in the pump design by interpreting the results as spectrum and statistical average, and finding co-relationship with vibration. It may be helpful for reliable operation of pumps.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Experimental Investigation of Unsteady Flow in a Vertical Shaft Axial Flow Pump

Araştırma Makalesi / Research Article

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ABSTRACT

Due to the changes in the system characteristics, pumps may have to be operated far away from the design point, such as in part-load or over-load operating points. Operating the pumps far away from the design point may cause fluctuations in the flow. As a result of the fluctuations mechanical problems in the pump structure may occur. In order to overcome the problem, the operating characteristics of the pump must be determined at part load operating conditions as well as design point operating condition. In this study, flow inside a vertical shaft axial flow pump is investigated experimentally. The experimental setup is designed and constructed for the laboratory tests. The pump which is designed and manufactured is tested in the test setup. The performance of the pump is determined by measuring the flow rate, inlet and outlet pressures, rotational speed and power input of the pump. The part load and over load operating regions are determined. Pressure variations are measured at various performance points with the piezoelectric pressure transducer placed in between impeller and diffuser blade passage. Simultaneously, comparisons are made with the vibration spectrums obtained in the pump.

Anahtar Kelimeler: Vertical shaft axial flow pump, piezoelectric pressure transducer, part-load flow, recirculation, flow-induced vibration.

Düşey Milli Eksenel Bir Pompada Zamana Bağlı Akışın Deneysel Olarak İncelenmesi

ÖZ

Sistem karakteristiğindeki değişimler nedeniyle pompalar tasarım noktalarının dışında, kısmi yükte veya aşırı yükte çalıştırılma durumunda olabilirler. Pompaların tasarım noktasının dışında özellikle önerilmeyen bölgelerde çalıştırılması birçok akış problemlerine sebep olmaktadır. Bunun sonucu olarak mekanik problemler meydana gelmektedir. Bu problemin üstesinden gelmek için pompanın tasarım noktasındaki karakteristiği yanı sıra kısmı yükteki çalışma koşullarının belirlenmesi gerekmektedir. Bu çalışmada, düşey milli eksenel bir pompanın içerisindeki akış deneysel olarak incelenmiştir. Laboratuvar testleri için deney düzeneği tasarımı yapılarak imal edilmiştir. Tasarımı ve imali yapılan pompa bu deney düzeneğinde test edilmiştir. Pompa performansını belirlemek için, debi ölçümü, pompa giriş-çıkış basınçları, pompa dönme hızı ve güç ölçümü yapılmıştır. Kısmı yük ve aşırı yük bölgeleri tespit edilmiştir. Çark ile difüzör arasına yerleştirilen piezoelektrik basınç algılayıcısı kullanılarak basınç değişimleri ölçülmüştür. Eş zamanlı olarak pompada elde edilen titreşim spektrumları ile karşılaştırmalar yapılmıştır.

Keywords: Düşey milli eksenel pompa, piezoelektrik basınç algılayıcısı, kısmi yük, döngüsel akış, akışkan kaynaklı titreşim

1. INTRODUCTION

Pumps are designed taking into account specific design parameters to operate at the best efficiency point [1-4]. In most plants, pumps operate in accordance with their design values. However, in some cases, system conditions may change over time. In this case, pumps operate at the points convenient with the performance characteristics according to the new system values.

Operating points far from the best efficiency point may cause unpredictable problems. The most important of these problems are flow-induced vibration and cavitation due to flow recirculation.

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When pumps operate at part-load, a flow phenomenon called recirculation occurs within the pump. This flow phenomenon affects the pump performance characteristic and often causes instability problems [5-6].

The instability in the pump flow-head characteristics is related to the unsteady flow in the pump. Rotor-stator interaction and inlet-outlet recirculation affect the pressure fluctuations and cause instability at the points below a critical flowrate.

Some of the extensive studies on pressure fluctuations were done by Gulich and Bolleter [1,7]. In these studies, the physics of pressure fluctuations and the rotor-stator interactions and the parameters affecting the pressure fluctuations are explained clearly. Bai et al. [8]

performed similar studies and showed the effect of number of blades on pressure fluctuations.

Internal flow in the pump instability region was studied by Braun [9] and Miyabe et al. [10].

Inlet recirculation and the parameters affecting recirculation were studied by Gulich and Bolleter [1,7], Oshima [11], Breugelmans and Sen [12].

Measurements can be performed from the rotating and non-rotating regions to experimentally examine the flow through the pump. Telemetry systems are needed to measure pressure variations on the impeller blades. Wulff [13] summarized the measurement methods of unsteady flow in the pump with studies found in the literature.

Unsteady flow in the pump can be measured with piezoelectric and piezoresistive pressure transducers. Kaupert and Staubli [14-16] compared the pressure fluctuations in a high specific speed pump with the numerical results obtained with the piezoresistive pressure transducers. Ulas and Karadogan [17] investigated the dominant frequencies with their laboratory experiments on horizontal centrifugal pumps. Comparisons were made with dimensionless parameters to examine the effect of design parameters on pressure fluctuation and vibration.

Spectrums are used to analyze unsteady measurement data. Obtained pressure and vibration variations are converted from time domain to spectrum domain by FFT (Fast Fourier Transform) method.

By the numerical calculation, Sun and Tsukamoto [18] investigated the rotor-stator interaction and obtained the flowrate in which the recirculation started. Tural [19] obtained the spectrums in the pump with CFD (Computational Fluid Dynamics) analyses and made investigations on the blade passing frequencies.

The probable faults in the pumps can be predicted in advance by experimental vibration analyses with the data of vibration spectrums. Studies on reliability and vibration in pumps are presented by Martins and Lima [20].

Khalifa et al. [21] and Sedlar et al. [22] investigated relationship between pressure fluctuations and vibration in their studies.

In some pump applications reliability is more important compared to conventional pump applications. Such as, Zhang et al. [23] studied on a nuclear reactor cooling pump. They made comparisons with different turbulence models and obtained the amplitude of the pressure at the blade passing frequencies.

In the literature, studies on pumps having radial impeller with diffuser and centrifugal pumps with volute are generally encountered. Experiments in these kind of dry running pumps (not immersed to water) are easier than the pumps running in the water like vertical shaft pumps. Axial type pumps are generally designed and operated as vertical with line shaft. In axial flow pumps the tendency to instability is higher than the low specific speed pumps due to the geometry of impeller.

Design changes at the impeller inlet can be applied to reduce the effect of inlet recirculation and improve the instability in axial pumps, successfully. Instability can be reduced by adding grooves to the inlet (Goltz et al. [24-25]) or a double-entrance structure (Flores et al. [26], Cao and Li [27]).

In this study, an axial pump with a specific speed of 2.8 rad/s at 560 l/s flowrate, 6 m head and 750 rpm was designed. After manufacturing and assembling, the experimental setup was designed to investigate the pressure fluctuations and vibrations.

Experiments were performed to obtain the performance curve of the pump. For different operating points pressure fluctuations and vibration data were obtained. Then the relationship between the pressure fluctuations and vibration data were determined according to different operating points. It is tried to determine the recirculation structure and contribute to the literature on this subject by examining the flow structure with laboratory experiments at different operating points for the pumps. It is aimed to get a test method to obtain the instability characteristics of the pumps.

2. DESIGN

After the pump design, CFD analyzes are done in computer environment. If necessary, some modifications on design are done according to CFD results. Decided final design is manufactured. Laboratory experiment results are compared with the CFD results. Such comparisons were made by Geerts [28], Weidong et al. [29].

In this study, the tested axial pump was designed using airfoil profiles, also known as the aerodynamic method [1-4]. In this method, the overall diameters of the impeller are calculated and determined for the desired design parameters. Airfoil profile selection and sizing of profiles are done in different sections of the blade for the targeted flowrate and head at the desired rotational speed of the pump. Design parameters of the pump, selected overall diameters and used airfoil profile of the impeller is given at Table 1. Blade structure and designed 4 bladed impeller is seen at Figure 1 and Figure 2.

After impeller design, the other parts of the pump were designed. The diffuser which guides the flow and suction bell were designed in accordance with the impeller. Design methods and details are available in the references [1-4].

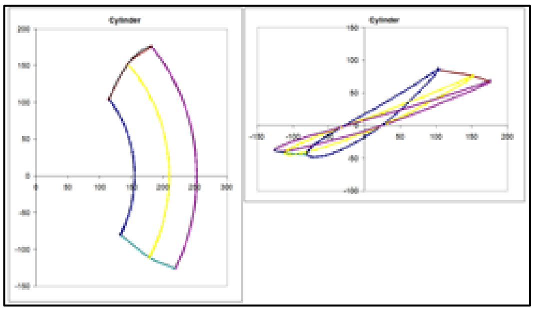

Figure 1. Blade structure of the impeller

Table 1. Design parameters of the pump, selected overall diameters and profile of the impeller

Flowrate (Q)	560	l/s
Head (H)	6	m
Rotational speed (n)	750	rpm
Specific speed	2.8	rad/s
Impeller diameter	505	mm
Impeller hub ratio	0.613	mm
Impeller hub diameter	310	mm
Profile	Gö623	

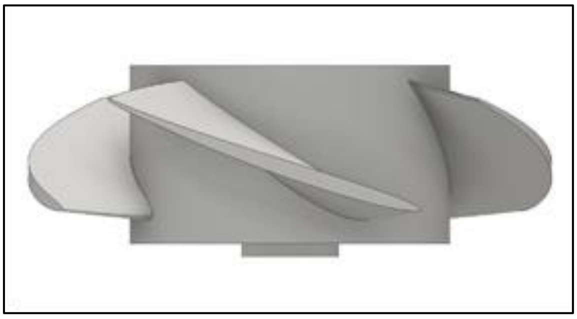

Figure 2. Designed impeller

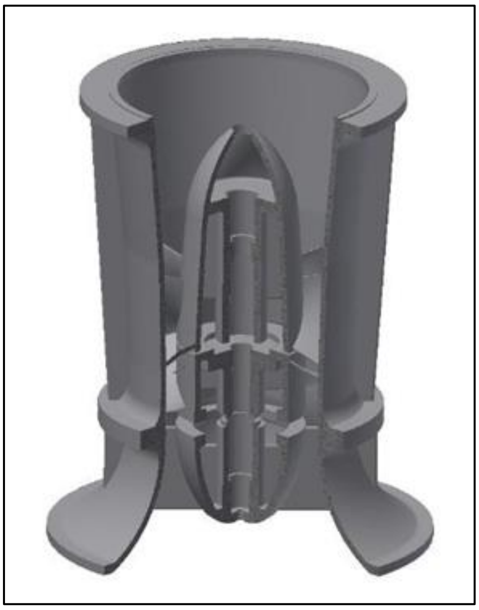

Figure 3. Designed pump

The designed pump is a vertical line shaft pump. Pump is immersed in water. There is a structure called the discharge head. This part is an elbow and carries the pump loads by bearings assembled on the discharge head. Motor which rotates the impeller is the top element of the pump system. Pump assembly and general assembly with all parts can be seen at Figure 3 and Figure 4.

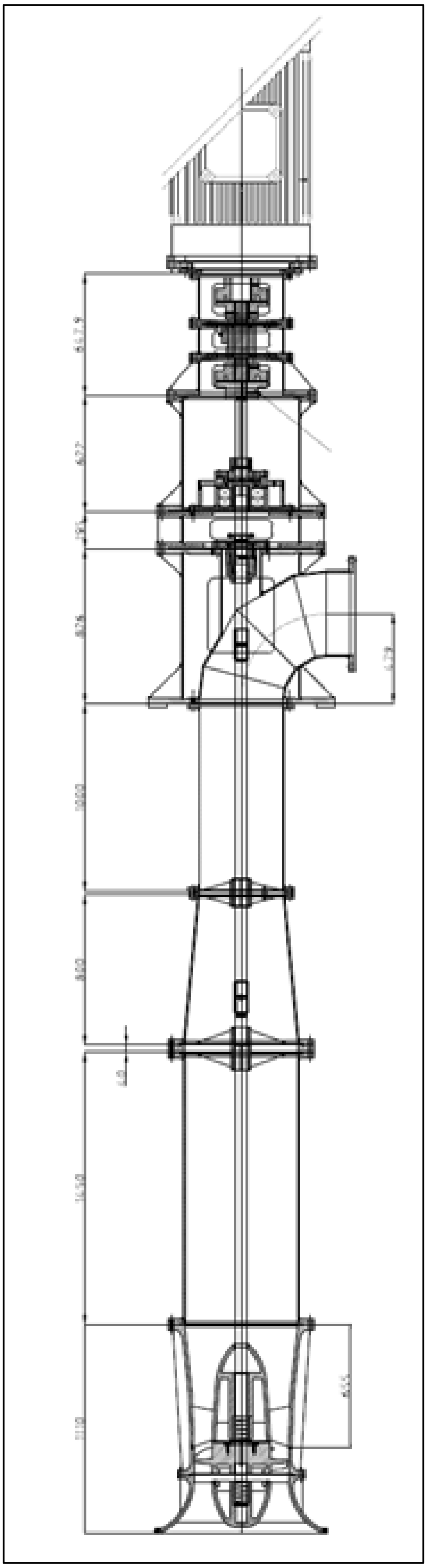

Figure 4. General assembly view

3. EXPERIMENTAL STUDIES

Laboratory experiments were performed at the Layne Bowler Pump Company. General pump performance tests are carried out by the use of electromagnetic flowmeters, pressure transducers, manometers and power analyzers. For this study required special measurement instrumentations which are related to the unsteady pressure measurements and vibration measurements are determined and provided.

Vibxpert II vibration analyzer was used for pressure fluctuations and vibrations measurements. The device has two channels. Time data can be obtained and converted to spectrums with this device which is originally used for vibration measurements and analysis. Vibration data can be collected simultaneously in two different directions from the pump bearings with its standard own accelerometer.

A piezoelectric pressure transducer that can measure dynamic pressure changes can also be connected to Vibxpert II analyzer. Kistler 603CBA-W model piezoelectric pressure transducer was used having 0-14 bar measuring interval.

Figure 5. Designed impeller

The pressure measurements location is under water so pressure and vibration sensors used in the study are waterproof with IP68 protection.

Figure 6. Piezoelectric pressure transducer

Figure 7. Accelerometer using at the diffuser

The used pressure transducer and its cable can be seen in Figure 6. During the tests, the sensor and the cable should not be damaged. For this, a protective shield is placed on the outside of the cable.

The pressure measurement location was determined to be downstream of the impeller blade. Piezoelectric pressure transducer was located between the impeller and diffuser blades which is at the midpoint of the diffuser blades in the circumferential direction.

Schematic figure of the tested pump and the measurement locations are given in Figure 8a and Figure 8b.

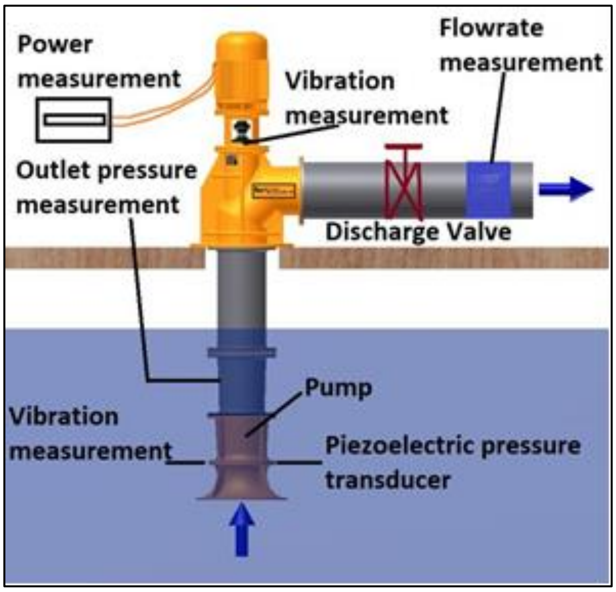

Figure 8a. Schematic figure of the tested pump

Figure 8b. Pressure measurement location (piezoelectric pressure transducer)

Figure 9a. Placing the pump to the test bed

Figure 9b. Placing the pump to the test bed

Figure 10. Measuring with Vibxpext II analyzer

The pump performance characteristics were obtained by collecting the flowrate, power and pressure data at the pump outlet while testing the pump. Flowrate is measured with an electromagnetic flowmeter. For pump total head calculation pressure is measured from the pump outlet. Distance between pressure transducer and water level is measured. The uncertainty in flowrate measurement is 0.2%, in pressure measurement is 1.49%, in power measurement is 1.95%. For pump efficiency the uncertainty is calculated as 1.96%.

In Figure 11, pump performance test results are given. The pump total head and efficiency is calculated as seen below.

Pump total head :

$$\mathrm{H} = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z$$

Q : Flowrate (m^3/s)

H : Pump total head (m)

P2 : Outlet pressure (Pa)

ρ : Density (kg/m^3)

V2 : Velocity at the pressure measurement location (m/s)

z : Distance between outlet pressure location and water level (m)

Pump efficiency :

$$\eta = \frac{\rho g Q H}{P_p}$$

Pp : Pump power (kW)

As seen in Figure 11, there is slope change in the flow-head curve starting from 400 l/s to 300 l/s in the pump performance characteristic. This is the region of instability for the pump. Best efficiency flow rate is 560 l/s.

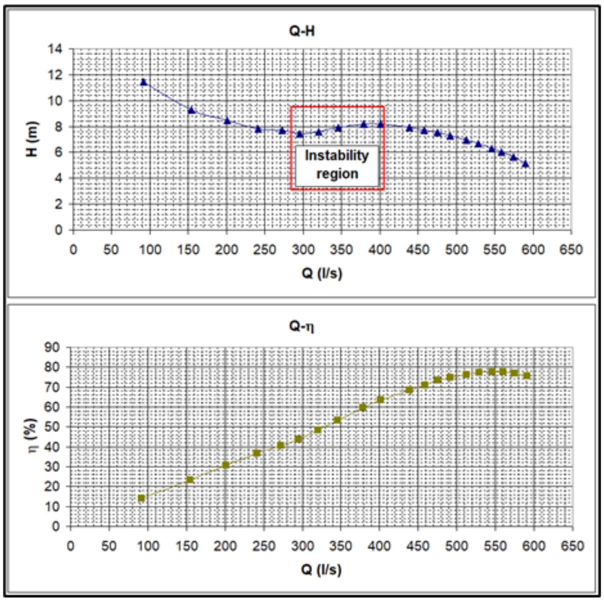

Figure 11. Pump performance test results (Flowrate-Head and Flowrate-Efficiency)

Pressure fluctuation data from the piezoelectric pressure transducer, vibration data from the accelerometer in the water and vibration data from the bearings were recorded in the form of time and spectrum at each flowrate in the performance characteristic.

The rotational speed of the pump was measured for each point. It rotates at approximately 747 rpm at each flowrate.

In this case, the operating frequency,

747/60 = 12.45 Hz

is obtained.

In Figure 12, the spectra taken from the analyzer for each flowrate in the performance characteristic of the pump are shown. As can be seen in the spectrum graph, the dominant frequencies which have the highest amplitudes at the spectrum at each operating flowrate are compatible with the operating frequency calculated above. Amplitude values at the frequencies of 12.45 Hz and its multiples are clearly visible at the spectrum graphs.

The number of impeller blades of the tested pump is four. The frequency associated with the flow, called blade passing frequency is calculated as,

12.45 x 4 = 49.8 Hz.

In order to determine the flow phenomena related to rotor-stator interaction and recirculation inside the impeller the blade passing frequency gives guiding results.

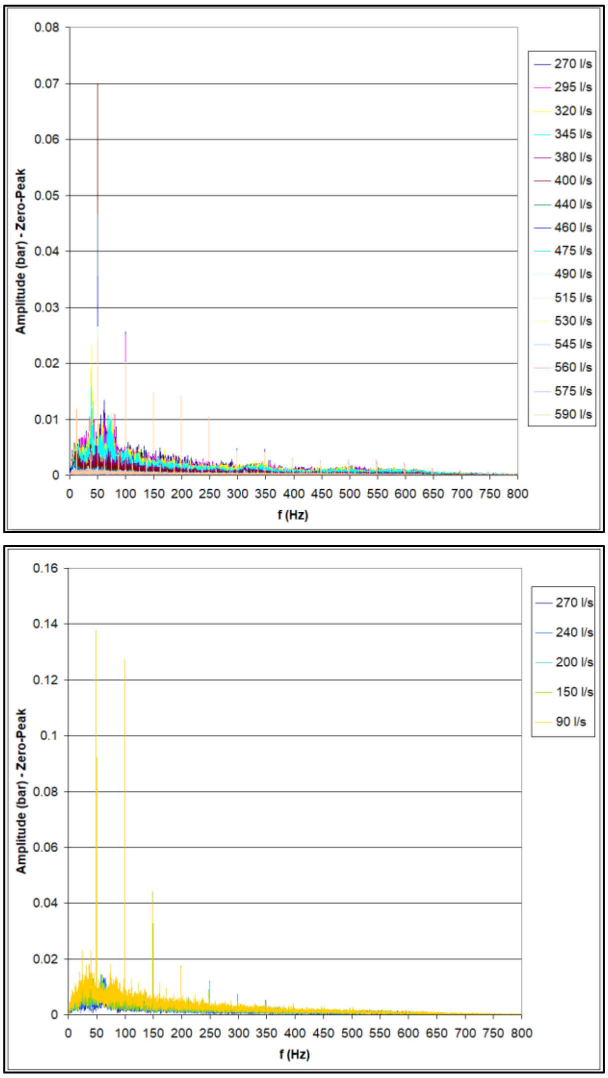

Figure 12. Collective display of the rotor-stator pressure spectrums obtained at each flowrate in the performance characteristic

In the spectrums given at the Figure 12, the highest amplitude frequencies were obtained at the 49.8 Hz at different flowrates. As moving towards to low flowrates, both amplitude values in the spectrum increased and amplitude values at frequencies in multiples of 49.8 Hz increased. Spectrums at some selected flow rates are shown in Figure 13. The amplitude values in flowrates close to the best efficiency flowrate are low in the whole spectrum compared to low flowrate spectrums. A complex spectrum view is observed at low flowrate operations. The amplitudes at 400, 440, 475 and 560 l/s operating frequency of 12.45 Hz, blade passing frequency of 49.8 Hz and its harmonics are seen clearly. At other frequencies the amplitudes are close to zero.

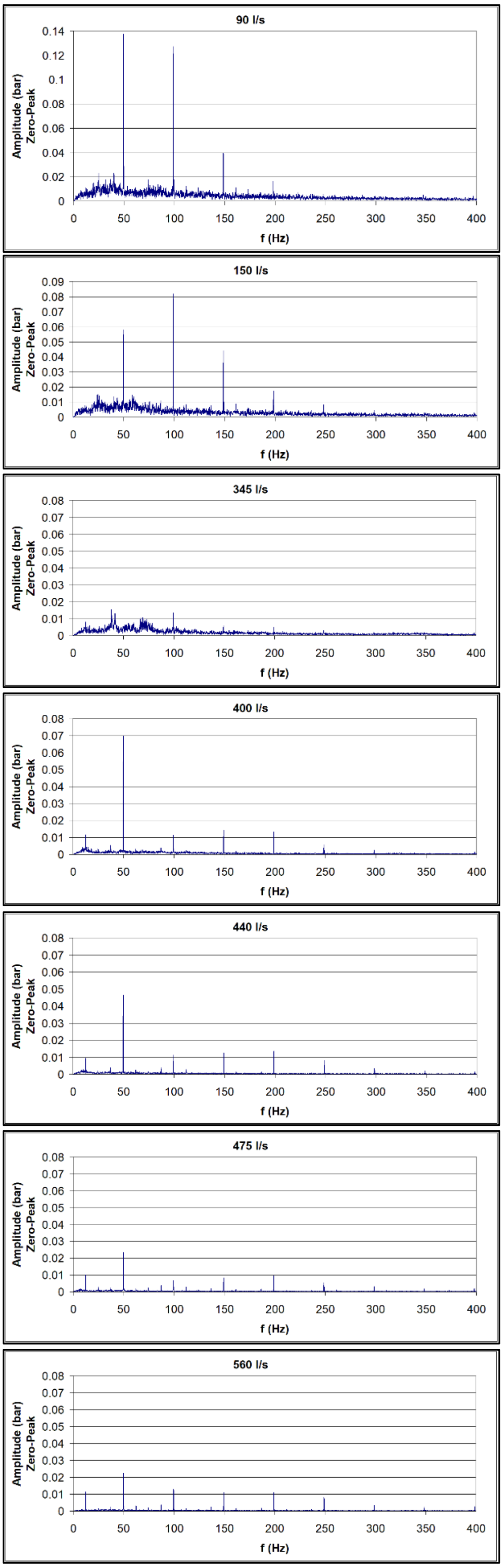

Figure 13. Pressure spectrums at 90, 150, 345, 400, 440, 475, 560 l/s

But, at 345 l/s, 150 l/s and 90 l/s other frequencies, the amplitudes increase at whole of the spectrum graphs. This spectrum change may give clue about flow inside the pump. Flow separations, turbulence, flow recirculation, vortices and noise are very low at the best efficiency flowrate. As expected, pressure spectrum become more complex at the flowrates far away from the best efficiency flowrate where unsteady flow is seen.

By analyzing the amplitude values of the spectrums and spectrum structure the flow phenomena inside the pump can be determined.

In Figure 14, the vibration spectrums obtained from the measurements taken in one direction from the bearing which carries the load of the pump is presented for 7 different flowrates.

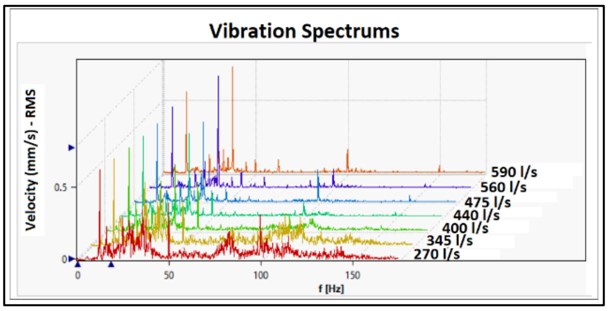

Figure 14. The vibration spectrums obtained from the measurements taken in one direction from the bearing at 7 different flowrates

In the obtained vibration spectrums, as in the pressure spectrums, amplitudes are increasing to the whole of the spectrum with decreasing flowrate. When interpreting the vibration characteristic, it is necessary to evaluate the many mechanical elements of the pump and their connections together, taking into account the hydraulic loads from the flow and their mechanical load effects. While performing vibration analysis, it is necessary to use basic parameters such as unbalance, eccentricity, bearing failures, resonance, flow-induced effects and cavitation. In this study, the blade passing frequency where flow-induced effects occur is emphasized. In Figure 14, vibration amplitudes at blade passing frequencies can be distinguished and these amplitudes increase towards low flowrates.

In order to guide the interpretation of the amplitude increases in the spectrums the peak-to-peak value of dominant frequency amplitude obtained for each flowrate is divided to the head value at that flowrate and defined as a percentage of fluctuation and shown in Figure 15.

According to the graph obtained, the percentage of fluctuation value tends to increase from 475 l/s to 400 l/s and decrease from 400 l/s to 345 l/s. The peak value occurring at 400 l/s in the fluctuation percentage graph is the first value that shows the effect of recirculation that has developed in the pump causing the beginning of instability at the performance characteristic. From this graph it can be determined that recirculation starts before the instability appears at the performance characteristic. The recirculation starts near the 475 l/s due to the change at the slope at the 475-400 l/s range at the fluctuation percentage graph. Generally, the flowrate at which the recirculation first starts is used as a limit of the Allowable Operating Range. It is concluded that the lower limit of the allowable operating flowrate at part-load for the pump is 84 % of the best efficiency flowrate.

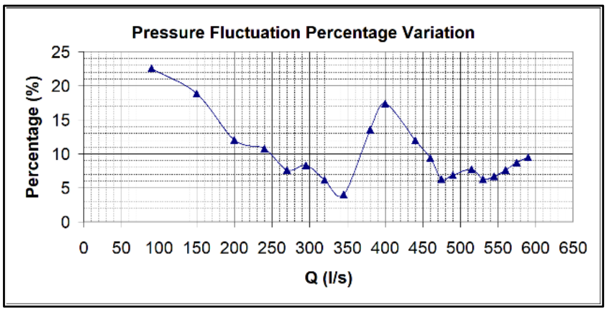

Figure 15. Pressure fluctuation percentage variation at different flowrates

In Figure 16, the time data of the pressure fluctuation obtained in one revolution of the impeller at the best efficiency flowrate is given. In this graph, the four-period event can be seen in relation to the number of impeller blades. As the time data becomes more complex towards low flowrates, it is difficult to distinguish the frequencies in the spectrum. However, the same clear values for vibration are not available in the time data obtained in the diffuser body. Considering the vibration data taken from the diffuser body in the water, the effects related to the flow could not be clearly understood. Therefore, the vibration data from the bearings were examined.

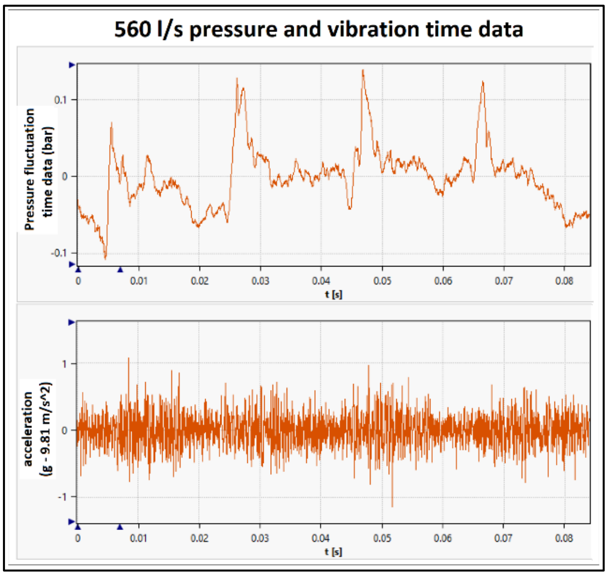

Figure 16. One revolution time data of pressure and vibration at best efficiency flowrate

Experimental data obtained in this study were also examined by considering statistical averages. In Figure 17, averages of pressure and bearing vibration time data are given for each flowrate using methods such as RMS (Root mean square), zero-to-peak, peak-to-peak.

Both pressure and vibration amplitude averages increased from the best efficiency point to the low flowrate. From the values in the graph, a slope change starting near the 450 l/s and an increase in the averages up to 300 l/s are seen. At 300 l/s, where the instability ends, there is a peak value formation in pressure. After decreasing the flowrate to 250 l/s, the average values tend to increase towards low flowrates, due to fact that flow phenomena become much more complex. Similarly, in vibration averages, near the 450 l/s is the flowrate at which slope changes begin. In this type of average graphs, interpretations can be made more clearly with the peak-to-peak values than others.

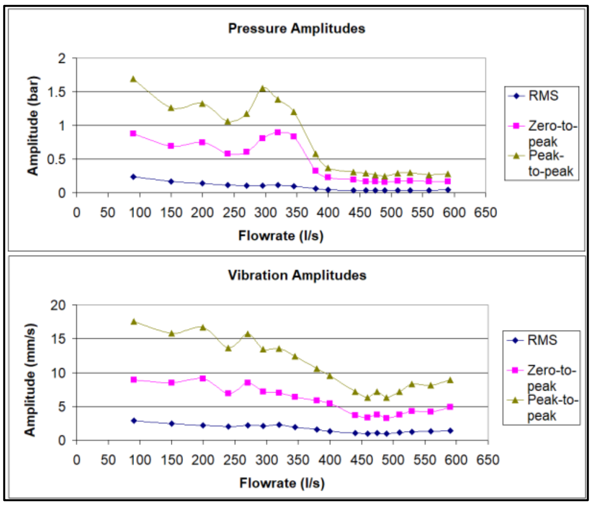

Figure 17. The statistical averages variation of pressure and vibration time data at different flowrates

As it is understood from the experimental results, it can be determined the flow problems that are occurred in which region of the pump characteristic can be determined by the method used in this study.

4. CONCLUSION

In this study, it is tried to examine how the flow conditions in a vertical line shaft axial flow pump affect the pump performance and its relations with instability by analyzing the amplitude and frequency changes in the pressure spectrum at different operating flowrates.

It is observed that the pressure and vibration amplitudes increase as the operating point move from best efficiency operating point to shut-off condition.

At critical flowrates the sudden amplitude change is observed from the spectrums, pressure fluctuation percentage and statistical averages. This critical flowrate is the early stage of the recirculation so instability does not start yet. But when the recirculation increases and the pressure fluctuation due to the rotor-stator interaction increases, instability region start to be seen in the performance curve. The critical flowrate is found to be 84 % of best efficiency point which is the lower limit of the allowable operation flowrate at part-load.

In order to reduce instability at part-load at design stage, effect of inlet elements, effect of inlet diameter to outlet diameter ratios, effect of blade profiles and thickness variations, effect of rotor-stator gap distance, effect of impeller and diffuser number of blades should be investigated.

According to the results obtained, it is possible to make improvements in the pump design by interpreting the results as spectrum and statistical average, and finding co-relationship with vibration. It may be helpful for reliable operation of pumps.

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DECLARATION OF ETHICAL STANDARDS

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Özgür CANBAZ: Designed the pump. Designed the pump setup and performed the experiments. Analysed the results and wrote the manuscript.

Prof. Dr. Nuri YÜCEL: Help as a supervisor to write the manuscript.

Prof Dr. Kahraman ALBAYRAK: Help as a supervisor to write the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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