Journal of Physics:
Conference Series

PURPOSE-LED
PUBLISHING™

OPEN ACCESS

Prediction of rotating stall within an impeller of a centrifugal pump based on spectral analysis of pressure and velocity data

To cite this article: Ulrik Ullum *et al* 2006 *J. Phys.: Conf. Ser.* **52** 36

View the article online for updates and enhancements.

You may also like

- Dynamic evolution of rotating stall in a model pump-turbine during runaway transient scenario: three-dimensional simulation
Xiaoxi Zhang and Qiuhua Chen
- Numerical investigation of radial thrust fluctuation caused by diffuser rotating stall in a centrifugal pump
Taiki Takamine and Satoshi Watanabe
- Experimental Study and Theoretical Analysis of the Rotating Stall in a Vaneless Diffuser of Radial Flow Pump
Y G Heng, A Dazin, M N Ouarzazi et al.

This content was downloaded from IP address 193.140.199.113 on 26/03/2026 at 08:43

Institute of Physics Publishing Journal of Physics: Conference Series **52** (2006) 36–45
doi:10.1088/1742-6596/52/1/004 Mathematics for Industry in Denmark

Prediction of rotating stall within an impeller of a centrifugal pump based on spectral analysis of pressure and velocity data

Ulrik Ullum[1], Jennifer Wright[2], Oguz Dayi & Ali Ecder[3], Azzeddine Soulaimani[4], Robert Piché[5] and Hemant Kamath[6]

[1] R & T, Grundfos Management A/S, Bjerringbro, Denmark, [2] University of Bath, United Kingdom, [3] Bogazici University, Turkey, [4] Ecole de Technologie Superieure, Canada, [5] Tampere University of Technology, Finland, [6] University of Southern Denmark, Sønderborg, Denmark.

E-mail: [5] robert.piche@tut.fi

Abstract. Experimental data, which was acquired in two centrifugal pumps and provided by Grundfos A/S, were analysed to determine if rotating stall could be detected from the velocity and pressure time series. The pressure data, which were uniformly acquired in time at high sample rates(10 kHz), were measured simultaneously in four adjacent diffuser channels just downstream of the impeller outlet. The velocity data, which were non-uniformly sampled in time at fairly low rates(100 Hz to 3.5 kHz), were acquired either in or downstream of the impeller. Two different methodologies were employed for detection of stall. The first method, which involved direct analysis of raw data, yielded qualitatively useful flow reversal information from the time series for the radial velocity. The second approach, which was based on power spectrum analysis of velocity and pressure data, could detect the onset and identify the frequency of rotating stall to a satisfactory extent in one of the two pumps. Nearly identical stall frequencies were observed in both velocity and pressure power spectra and this rotating stall phenomenon, which occurred at a very low frequency relative to the impeller speed, did not reveal any noticeable degree of sensitivity to the flow rate. In the other pump, where the available data was limited to velocity time series, the power spectrum analysis was successful in detecting stationary stall for a 6 bladed impeller but did not provide conclusive results for the existence of stall in the case of the 7 bladed impeller. Recommendations on the type of experimental data required for accurate detection of stall are provided based upon the present study.

Keywords: Time series, rotating stall, centrifugal pump.
PACS: 06.30Ft, 47.80.
MSC: 76-05, 37M10.

1. Introduction

When a pump operates at reduced flow rates, its performance could get degraded by the inception of flow instabilities such as stationary and rotating stall phenomena. Stall refers to zones of recirculating fluid within some flow passages of a pump's components(e.g. impeller, diffuser or volute) and this can cause substantial velocity and pressure fluctuations which can not only adversely affect the flow but the pump as well. These zones could propagate along the circumferential direction of the impeller or diffuser and it is then referred to as rotating stall. The rotating-stall mechanism is not yet very well understood, even though a qualitative explanation of propagation, based upon cascade theory, was proposed by Emmons et al. [1] more than 40 years ago.

© 2006 IOP Publishing Ltd

Although rotating stall may occur in any turbomachinery component, this phenomenon is most frequently studied in compressor rotor-blade passages. In centrifugal pumps, experimental studies([2]-[4]) indicate the existence of rotating stall in the impeller and in the diffuser/volute and in both for some geometries. Computational studies of stall prediction in industrial centrifugal pumps are limited primarily due to the difficulties in modelling turbulent separated flows in complex geometries that involve interactions between rotating and stationary components. A combined experimental and computational study carried out recently([5]-[6]) reveals that upstream influence of stationary stall can introduce a swirl component in the inlet velocity profile. This upstream influence can adversely affect predictions from large eddy simulations(LES), which did not account for the inlet distortion since it was not possible to experimentally measure it. It was also shown that in contrast to LES, Reynolds-averaged Navier-Stokes(RANS) simulations did not even predict the existence of stationary stall phenomenon with either of the two turbulence models which were tested in this study. Accurate computational prediction of stall is largely dependent on user-specified input such as boundary conditions, transition and turbulence modeling, computational domain that needs to be defined for a realistic representation of the actual configuration among others, which depend upon details that often can be provided only by conducting experiments.

Reliable detection of stall in industrial centrifugal pumps can then be more directly based on actual experimental measurements. Furthermore, different experimental techniques of varying complexity can be employed in order to furnish data suited for stall detection. Evidently, the simplest and the least time consuming, but yet reliable, technique is preferred.

2. Formulation of the Problem

The primary objective of this study was to develop a simple method that predicts the presence of rotating stall within an impeller of a centrifugal pump based upon time series or reduced data sets of measured mean-velocity and pressure data. Experimental data acquired in two pumps, CR90 and CR4x2, were available for analysis. For the CR4x2 pump, data was acquired for two different configurations, namely, with a 6-bladed and a 7-bladed impeller. The methodologies to be proposed for stall detection will be closely related to the nature of the available experimental data. Therefore a brief introduction to the measurement techniques and equipment used in this study, shall be given hereafter.

Laser Doppler Velocimetry (LDV) is a non-intrusive optical technique for measuring velocities in transparent fluids. An intereference pattern is obtained by intersecting two coherent laser beams and neutrally-buoyant particles, which are seeded into the flow, will scatter a signal when passing the beam intersection. The emitted signal is processed by the LDV system and converted to a signed velocity. Due to the stochastic arrival times of the particles passing through the measurement volume, the velocity time series obtained will have non-uniform time intervals between samples. The measurement system used for both the CR4x2 and the CR90 pumps is a two velocity-component back-scatter system from Dantec Dynamics with a 300mW air cooled Argon-ion laser and two BSA enhanced processors.

Apart from a transparent fluid, the LDV technique also requires a fully transparent flow rig in the regions of interest. Fig. 1 shows two images from the CR4x2 setup. It can be seen that the front and back plate of the pump housing, the hub and shroud of the impeller and the diffuser front plate are all made of either perspex or glass. This construction enables LDV measurements in a large part of the pump housing. The inlet and outlet pipes are also equipped with glass windows allowing for measurements of the velocity profiles at these locations.

On the CR90 pump, the optical access has been limited due to a very complex geometry and LDV measurements are only possible through windows or prisms in the geometry as it can be seen in the CAD illustration (Fig. 2).

In the CR4x2 pump, the velocity data used in the present study were acquired within the rotating impeller at a radial position of $0.9R_{imp}$, where R_{imp} denotes the impeller radius, and pressure data are not available. In this case, the sampling is phase-resolved i.e. velocity samples were sorted into

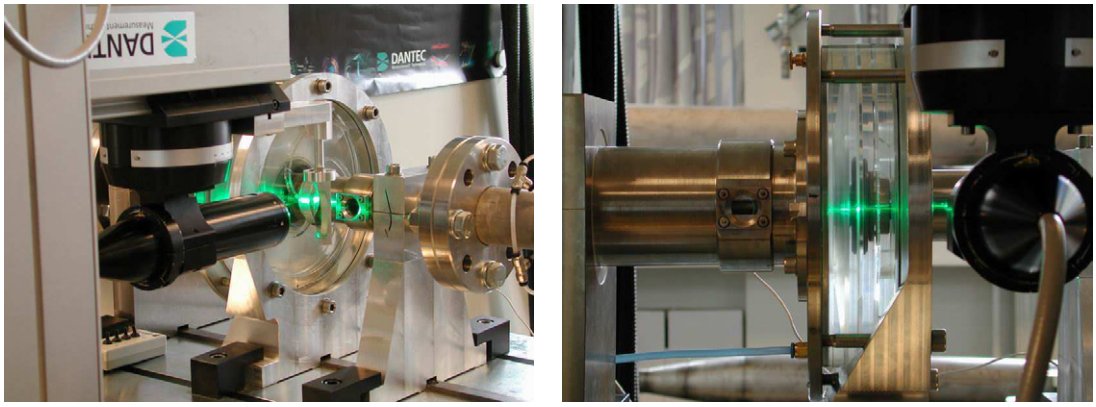


Figure 1. Images of CR4x2 test pump and LDV measurement optics

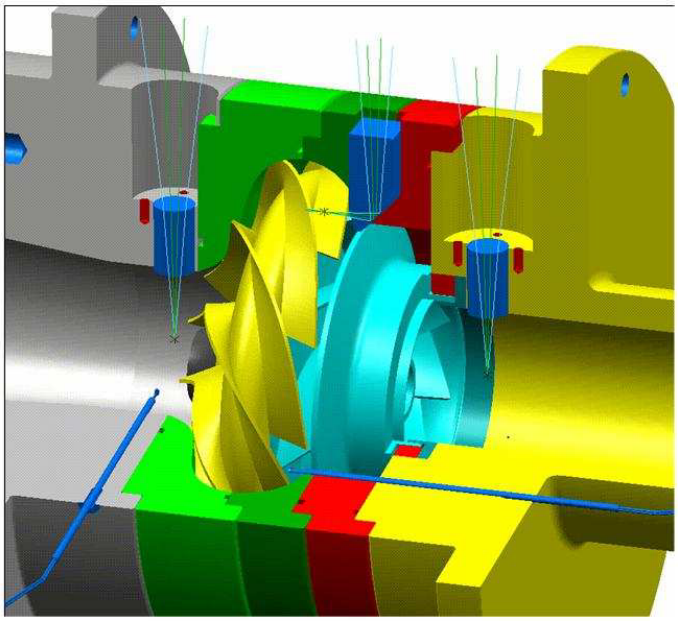


Figure 2. CAD illustration of CR90 pump and its optical windows for data acquisition

360 angular bins based on their arrival time relative to a once-per-revolution pulse. In each bin, mean velocity vectors were calculated based on approximately 500 individual samples. It should be noted that this bin-averaging technique can be employed for diagnosing stationary but not rotating stall.

However, in the CR90 pump, LDV data is acquired immediately downstream of the impeller (see Fig. 2). Pressure data, which were uniformly sampled in time, were acquired simultaneously in 4 adjacent diffuser-channel entrances just downstream of the impeller outlet. For pressure measurements, four fast-response Kulite pressure transducers have been used in conjunction with an MGC amplifier and a four-channel Tektronix digital oscilloscope for data acquisition. This completes a brief description of the measurement techniques employed in the present study.

The performance curves of the CR90 pump and CR4x2 pumps, with 6 and 7 bladed impellers, are shown in Fig. 3. It can be observed that the CR90 performance curve reveals a distinct loss of smoothness below a flow rate of 40 m^3/h and as a result would indicate a likelihood of onset of stall. In contrast, the

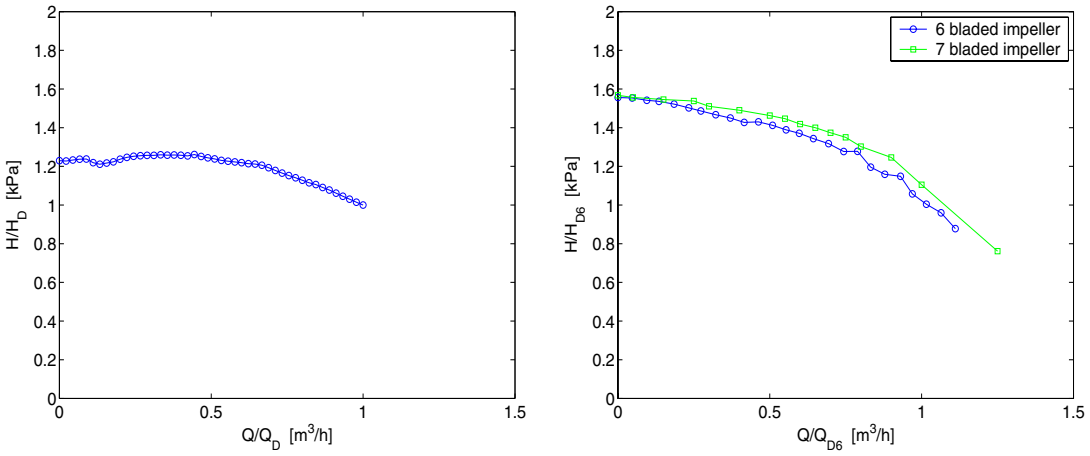


Figure 3. Performance curves : (i) CR90 pump (ii) CR4x2 pumps with 6 and 7 bladed impellers.

performance curves for CR4x2, for both 6 and 7 bladed impellers, are relatively smoother and less flat at low flow rates.

3. Proposed Methodologies for Detection of Stall

Two different methodologies were proposed for detection of stall by analysis of pressure and velocity time series acquired from the two pumps. First, the raw data were analysed directly by breaking up the time series into time-periodic strips, assuming constant angular velocity of the impeller, and aligning these strips by introducing a third coordinate to generate a carpet plot of velocity/pressure data. It may then be possible to identify some flow feature, which is a manifestation of rotating stall, as it propagates from one blade passage to the next. Flow reversal could be detected in the time series by monitoring the sign of the radial velocity.

In the second approach, motivated by the results reported in [4], spectral analysis of uniformly sampled pressure and non-uniformly sampled velocity data were to be carried out to determine if the stall frequency could be clearly identified. The stall propagation frequency could be as low as 5-10 % of the impeller speed as reported in [3]-[4] and hence the success of this method would depend upon accurate resolution of low-frequency content of the power spectra corresponding to velocity and pressure time series.

4. Results and Discussions

At the outset, an order-of-magnitude analysis was performed to estimate the stall propagation frequency for each of the two pumps. This required proposing a mechanism that enables the calculation of residence time for a stall cell in a blade passage prior to its propagation to the one adjacent to it. The stall-cell residence time was taken to be of the same order as the flow residence time i.e. the time it takes a fluid particle to traverse the extent of the impeller blade. With a radial velocity of the order of 10 m/s and a blade camber line of order 0.25 m, a residence time of 0.025 seconds is obtained which implies that in 1 second the stall cell would have propagated 40 impeller blades. This would correspond to a stall propagation frequency of about 6 Hz since each of the two pumps has approximately the same number of blades in the impeller(6/7 blades). The geometry and operating parameters for the two pumps are indicated in the table below.

An order-of-magnitude estimate of stall-propagation frequency is an important step in the detection of stall. It should be mentioned that data acquisition for the CR90 pump was much more extensive as compared to CR4x2 pump. Not only were pressure and velocity time series acquired for CR90 pump,

Table 1. Relevant Geometry and Operating Parameters for the Two Pumps

Pump Code	Design Flow Rate	Impeller Speed	Impeller Blades	Diffuser Vanes
CR90	90 m^3/h	50 Hz	7	11
CR4x2	10.8 m^3/h	12.1 Hz	6/7	4

whereas data acquired for the CR4x2 pump was limited to velocity time series, but many more off-design conditions were monitored as well.

4.1. Analysis of CR90 data

The first approach that involved generating a carpet plot of raw data, which would reflect its inherent periodicity, did not provide much useful information for the detection of stall. The pressure and velocity data for a turbulent flow has a continuous variation of time scales and it was not possible to discern any meaningful low-frequency pattern in the carpet plot which could have been interpreted as a manifestation of stall.

Subsequently, a flow reversal index was constructed for each revolution of the impeller which would indicate the fraction of data samples with negative radial velocity. Thus, an index of 0 would indicate that all sampled data have positive velocity whereas an index of 1 corresponds to all negative radial velocities for an impeller revolution. The flow reversal index for the CR90 pump is shown in Fig. 4 for 1000 impeller revolutions and for flow rates ranging from 15 m^3/h to 65 m^3/h. It is observed that at a flow rate of 25 m^3/h, quite a few impeller revolutions have a flow reversal index greater than 0.5 which would indicate a likelihood of stall occurrence. However, this method does not provide conclusive evidence of stall nor does it provide any means to estimate the stall propagation frequency.

In the second approach, power spectra of pressure and velocity time series were calculated and plotted as a function of frequency. The pressure data, which is uniformly sampled in time, was analysed using Matlab's power spectral density script. The velocity data, which is non-uniformly sampled in time, required a Matlab script [7] that is based on the technique proposed in [8].

The spectral analysis methodology for unevenly spaced data developed in [8] slightly modifies the conventional definition of power spectrum to retain the simple statistical behaviour of the evenly spaced case. It is shown that with the modification, power spectrum analysis and least-squares fitting of sine waves to the data are exactly equivalent. An important practical consequence is that the modified procedure is better suited for detecting a periodic signal in the presence of noise.

It was decided to initially examine the power spectra for design conditions (90 m^3/h) corresponding to the CR90 pump to identify the various frequency peaks that are revealed in the radial and tangential velocity data. The most pronounced peak in the two spectra in Fig. 5, which are shown up to 500 Hz, corresponds to impeller blade passage frequency(50 Hz x 7 blades) that is clearly observed at 350 Hz. The impeller frequency at 50 Hz and several of its super harmonics, particularly those at 100 Hz and 150 Hz, can also be identified in this figure.

To detect stall at off-design conditions, the power spectrum was plotted up to 50 Hz so that the low-frequency region can be examined in considerable detail. In Fig. 6, the power spectra for radial and tangential velocities are shown for a low flow rate of 15 m^3/h where rotating stall is expected to occur. A pronounced spike at 3 Hz can be clearly observed in both power spectra and several other significant spikes can also be seen in the neighbourhood of this frequency. The value obtained is in agreement with the order-of-magnitude estimate of the rotating stall frequency obtained earlier.

At a slightly larger flow rate of 25 m^3/h, where rotating stall is expected to persist, the power spectra for the two velocity components are shown in Fig. 7 and the pronounced spike appears shifted slightly lower at about 2 Hz.

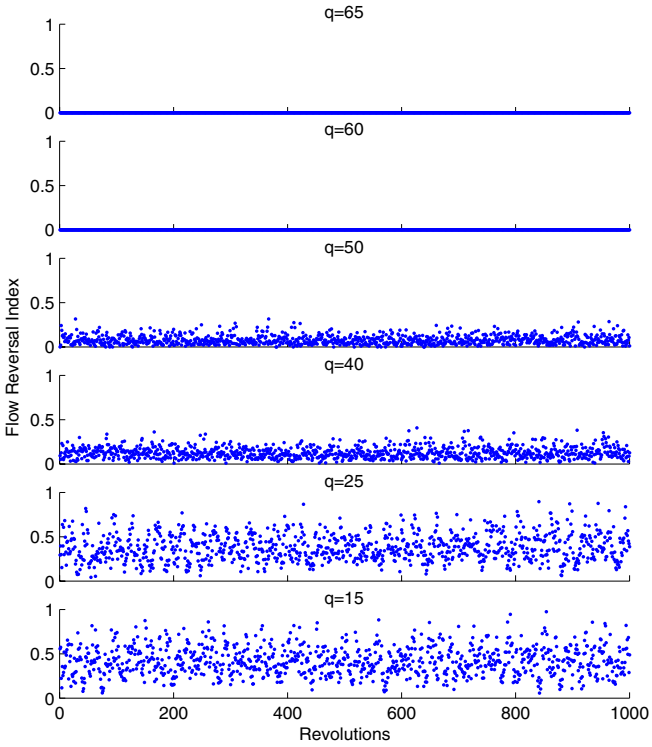


Figure 4. Flow reversal index based on the radial velocity for CR90 pump

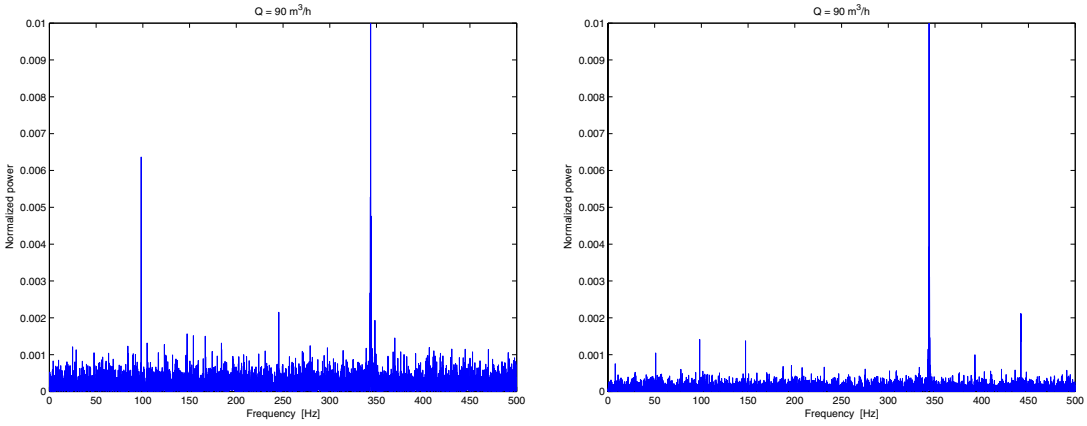


Figure 5. Power spectra at design conditions : (i) radial velocity (ii) tangential velocity

However, at a flow rate of 40 m^3/h, neither of the two velocity power spectra exhibit any noteworthy spike that can be interpreted as a manifestatation of rotating stall but the plots are not shown here to conserve space. It can then be conjectured that rotating stall appears somewhere in between a flow rate of 25 m^3/h and 40 m^3/h but there are no velocity measurements available at intermediate flow rates which can be used to further localize the onset of stall.

Pressure data, however, were acquired at intermediate flow rates for the CR90 pump. The power spectra for pressure data at flow rates of 25 m^3/h, 30 m^3/h, 35 m^3/h and 40 m^3/h are shown in Fig. 8, which clearly reveals a prominent spike at the lowest flow rate confirming the presence of rotating stall

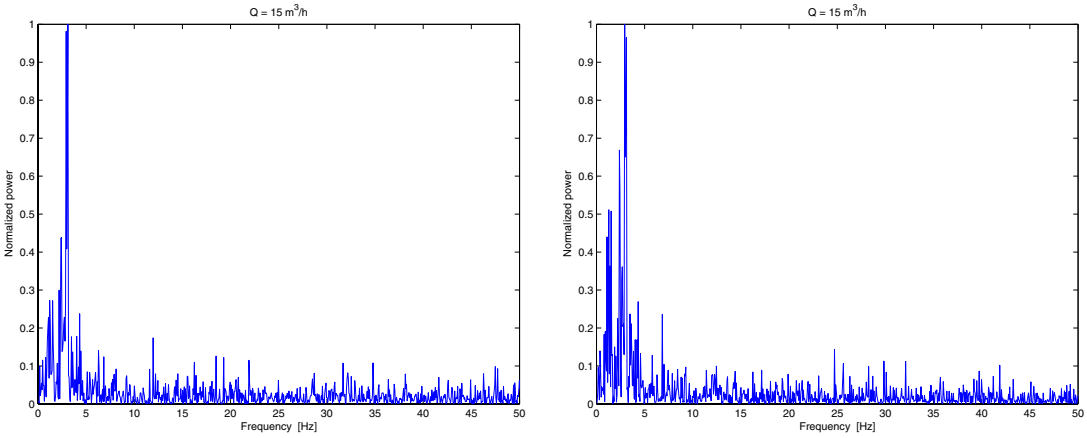


Figure 6. Off-design (15 m^3/h) power spectra : (i) radial velocity (ii) tangential velocity

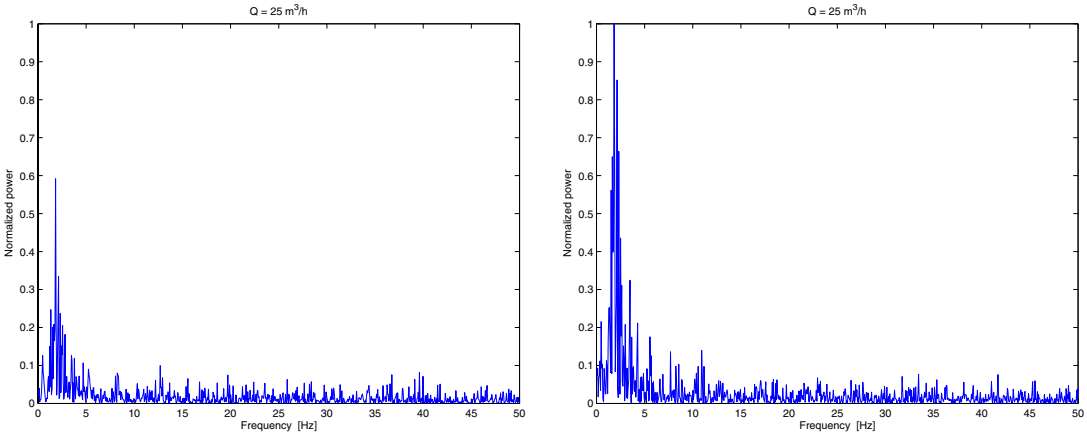


Figure 7. Off-Design (25 m^3/h) power spectra : (i) radial velocity (ii) tangential velocity

at a frequency of 2 Hz. It can also be inferred that rotating stall is absent at a flow rate of 40 m^3/h and to a less certain extent at 35 m^3/h as well. The power spectrum for a flow rate of 30 m^3/h reveals a large number of spikes which are not amenable to a straightforward interpretation; it is not clear if stall is present at this flow rate and whether it is stationary or rotating.

It would thus be prudent to conclude that the onset of rotating stall in the CR90 pump takes place somewhere in the neighbourhood of 30 m^3/h.

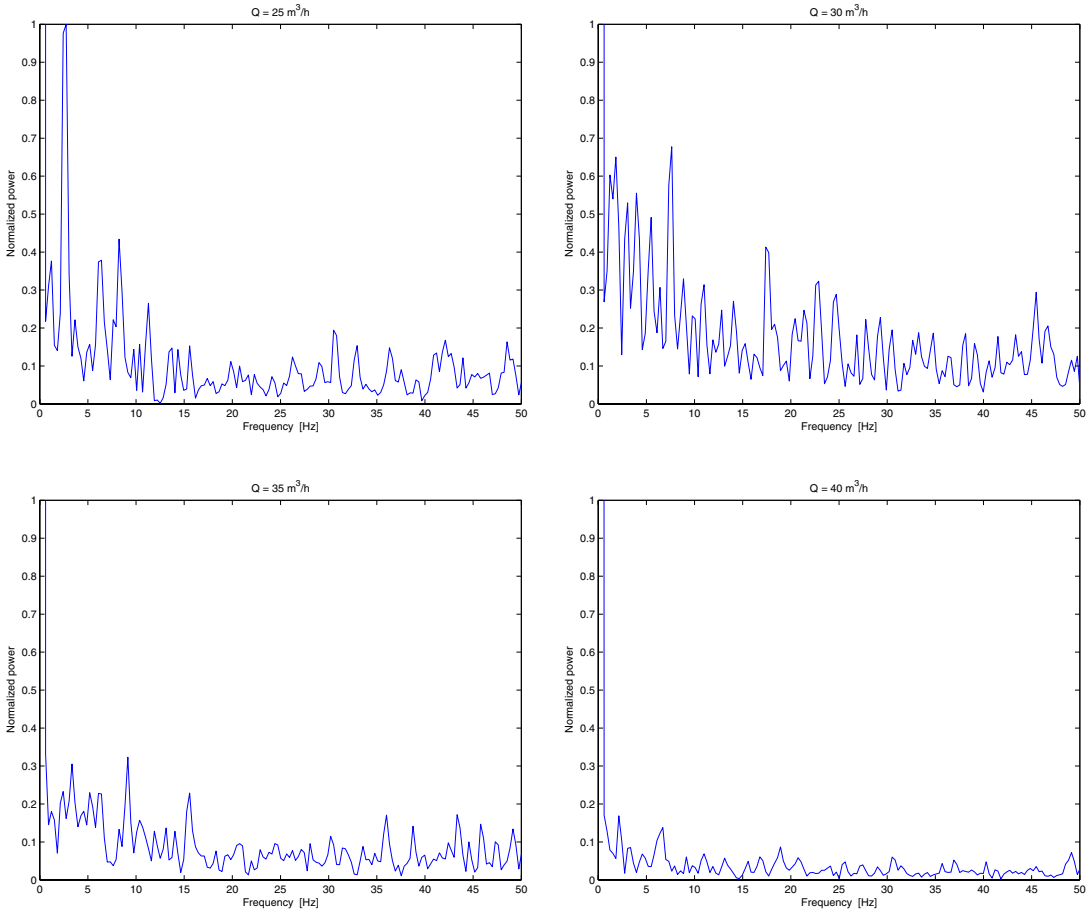


Figure 8. Pressure power spectra ; top left : 25 m^3/h, top right : 30 m^3/h, bottom left : 35 m^3/h, bottom right : 40 m^3/h

4.2. Analysis of CR4x2 data

Stall analysis, which was carried out in this study, for the CR4x2 pump was rather restricted in scope since limited data was acquired for this pump and the performance curve in Fig. 3 did not reveal any pronounced degradation at low flow rates for either of the two impellers. A stationary stall, however, was identified earlier for the 6 bladed impeller at an off-design flow rate of 2.7 m^3/h, and this was detected by an angular bin-averaging technique. It turns out that every alternate impeller blade passage gets stalled which is also reflected here in the power spectra for the tangential velocities in Fig. 9 corresponding to design and off-design conditions. Comparison of the two power spectra indicates that the impeller-blade passage frequency of 72.6 Hz (12.1 Hz x 6 blades) is reflected in both plots whereas a spike at half that value in the off-design case is due to stall cell periodicity.

Fig. 10 contains the tangential velocity power spectra for the 7 bladed impeller at design and off-design conditions. The impeller-blade passage frequency, which is now larger at 84.7 Hz (12.1 Hz x 7 blades), is clearly seen in both plots. However, the off-design case has several additional spikes and the plot appears noisier due to a factor of 4 magnification of the ordinate values relative to the design case. In the off-design spectra, the spikes at 39 Hz and 47 Hz are not subject to a straightforward interpretation even though the latter value is close to 48.4 Hz, which would correspond to an upstream influence of the diffuser vanes(12.1 Hz x 4 vanes). It is evident that a stationary stall cannot be sustained in the blade

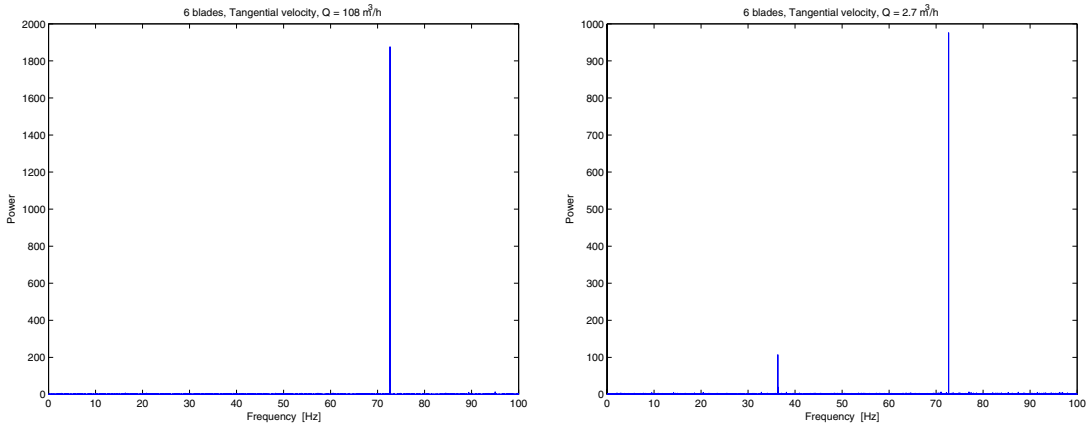


Figure 9. Tangential velocity power spectra (6 bladed impeller) : (i) 10.8 m^3/h (ii) 2.7 m^3/h

passages due to a loss of periodicity introduced by the odd number of impeller blades. The absence of a spike at frequencies below 12.1 Hz, which stands distinct from the background turbulent spectra, would largely rule out the existence of a rotating stall. It can then be stated that the analysis of time series for the 7 bladed configuration of the CR4x2 pump does not reveal any clearly identifiable stall frequency and this is also reflected in the smoother performance curve in Fig. 3 when compared to the 6 bladed case.

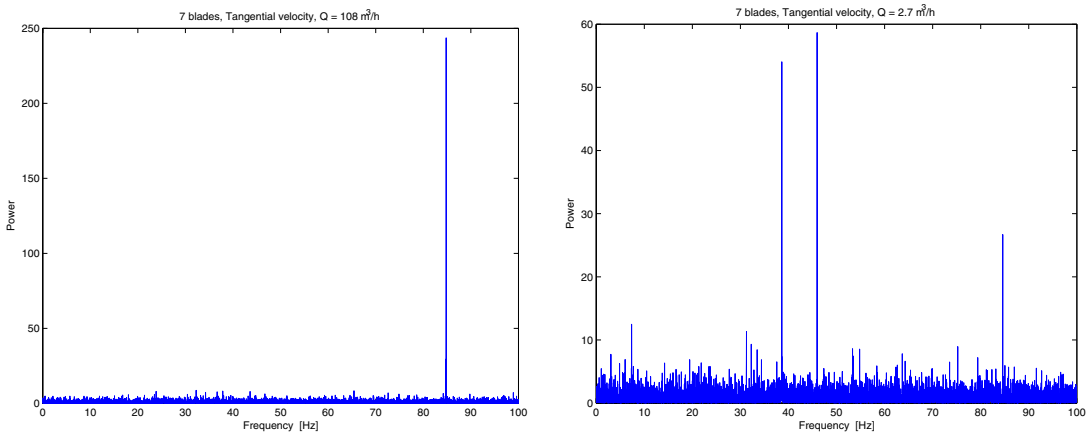


Figure 10. Tangential velocity power spectra (7 bladed impeller) : (i) 10.8 m^3/h (ii) 2.7 m^3/h

5. Conclusions

An analysis of rotating stall, based on experimental data provided by Grundfos A/S, was carried out. The data available for this study were pressure and velocity time series, acquired in or immediately downstream of the impeller in two different centrifugal pumps.

Two methodologies for detecting stall, based on the available experimental data, were proposed. In the first method, the time series were partitioned into strips based on the impeller revolution time and these strips were aligned to enable identification of a propagating pattern in the resulting carpet plot. However, no patterns were directly identifiable from the noisy plots due to the inherent fluctuations

present in a time series for turbulent flow. A flow reversal index was generated, which would indicate the fraction of samples in each impeller revolution having negative radial velocity, that provided some qualitatively useful flow reversal information. However this method was limited in scope since it could neither directly detect stall nor a stall frequency.

The second method involved the analysis of power spectra corresponding to the velocity and pressure time series in order to determine if the stall propagation frequency, which is expected to occur in the low frequency part of the spectrum, could be isolated and accurately resolved. This method was successful in indicating if the pump was stalled or not and to some extent in identifying the frequency of rotating stall and the flow rate at which onset of stall occurs. However, not all of the data analysis for the two pumps yielded results which indicated the presence of stall. The velocity data from the CR90 pump were better conditioned and a flow rate of around 30 percent of the design value was identified as the location of stall onset. Furthermore, a stall frequency as low as 2 Hz, which is about 5 percent of the rotation frequency of the impeller, was found from the velocity power spectra. The power spectrum analysis for pressure data confirmed the results found in the velocity spectra. In the case of the CR4x2 pump, the occurrence of stationary stall phenomenon, which was detected by Pedersen et. al [5] for the 6-bladed impeller, was verified in this study from the power spectra. Nevertheless, there was no clearly identifiable stall frequency in the velocity spectra corresponding to the 7-bladed impeller for the CR4x2 pump.

Static pressure measurements, with transducers mounted flush with the wall, are significantly more convenient as compared to LDV measurements. Not only are sampling rates much higher for pressure measurements but more importantly this technique does not require a transparent test rig for data acquisition. The present study indicates that rotating stall frequency can be detected by spectral analysis of pressure time series just as well as velocity time series. However, more noise in the pressure spectra leads to less conclusive results and improvements may then be necesssary for future applications of this technique. The sampling frequency of 10 kHz might be too high for the scope of this work considering the frequency range of interest for stall detection. Stationary and rotating stall phenomena both occur at frequencies below the blade passage frequency and thus the sampling frequency can be adjusted accordingly using the Nyquist criterion. Furthermore, with some additional effort the utility of a dynamic pressure probe, located just outside the impeller, could be investigated as a device for stall detection. Spectral analysis of dynamic pressure could yield more prominent peaks and less noise which is very much desired at a flow rate corresponding to the onset of stall. However, this needs to be investigated further in order to characterize the performance of this intrusive measurement device for stationary and rotating stall detection.

Acknowledgments

This study was partially supported by Grundfos A/S, Bjerringbro, Denmark.

[1] Emmons H W, Kronauer R E and Rockett J A 1959 A survey of stall propagation-experiment and theory *ASME J. Basic Eng.* **81** 409-16

[2] Lennemann E and Howard J H G 1970 Unsteady flow phenomena in rotating centrifugal impeller passages *ASME J. Eng. Power* **92** 65-72

[3] Yoshida Y, Murakami Y, Tsurusaki T and Tsujimoto Y 1991 Rotating stall in centrifugal impeller/vaned diffuser systems *Proc. First ASME/JSME Joint Fluids Engineering Conference* **FED-107** 125-30

[4] Sinha M, Pinarbasi A and Katz J 2001 The flow structure during onset and developed states of rotating stall within a vaned diffuser of a centrifugal pump *ASME J. Fluids Eng. 123* 490-99

[5] Pedersen N, Larsen P S and Jacobsen C B 2003 Flow in a centrifugal pump impeller at design and off-design conditions-part I: Particle Image Velocimetry(PIV) and Laser Doppler Velocimetry(LDV) measurements *ASME J. Fluids Eng. 125* 61-72

[6] Byskov R K, Pedersen N and Jacobsen C B 2003 Flow in a centrifugal pump impeller at design and off-design conditions-part II: Large eddy simulations *ASME J. Fluids Eng. 125* 73-83

[7] http://wise-obs.tau.ac.il/∼eran/MATLAB/Timeseries.html

[8] Scargle J D 1982 Studies in astronomical time series analysis. II. Statistical aspects of spectral analysis of unevenly spaced data *Ap. J. 263*, 835-853