Stall identification methods in centrifugal compressor

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Abstract. The presented paper describes a method for detecting compressor stall precursors in a measured pressure signal using procedures arising from the chaos theory. The experiment was carried out on a scaled-down model of a compressor used in natural gas transportation. It was a single-stage centrifugal compressor with a vane diffuser. The presented method is based on the analysis of an attractor constructed using the time delay method from the pressure signal collected at the compressor outlet flange at a frequency of 25 kHz. Using a parameter called correlation dimension, we identified small changes in the dynamics of the measured signal before the onset of negative stall manifestations. In general, it was found that near the stall curve there were minor disturbances in the flow field in the compressor, due to which the correlation dimension decreased.

1 Introduction

A significant part of gas transit between the eastern and western parts of Europe is carried out through the territory of the Slovak Republic. For this reason, there are several high-capacity compressor stations, which provide compensation for hydraulic losses in the pipeline. The key technical equipment of these stations is the compressor. As the compressor station has to adapt the instantaneous gas supply to the needs of the receiver, the compressors operate over a wide range of flow rates, with the risk of the compressor going into stall or surge mode at low flow rates.

Stall is a phenomenon that is manifested externally by an increased vibration rate and as such is undesirable. Vibration of the mechanical parts of the compressor can lead to damage to the compressor and can also be transmitted to other parts of the compressor station, such as piping, which may resonate with it, causing damage or endangering the safety of personnel.

In terms of compressor performance, there is a drop in compression ratio with mild stall, but cyclical changes in operating point can occur with more severe stall symptoms. This situation can be dealt with by increasing the flow rate by using an anti-surge valve. For compressors with a large hysteresis loop, compressor blockage can occur when a return to normal operation cannot be realized without shutting down the compressor [1].

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In terms of physical processes, we can distinguish several types of stall. Spike-stall is associated in the literature with flow instabilities in impeller tip clearance. During the flow decreasing, a secondary flow occurs between the pressure and suction sides of the blade, resulting in the formation of vortices, travelling in the circumferential direction to the following blade. The interaction of the traveling vortices with this blade causes a change in the angle of attack which is considered as a spike-stall trigger [2, 3]. More recent research work, based on PIV measurements, suggests that spike-stall originates from the detachment of the flow from the blades due to traveling vortices [4]. Another factor contributing to spike-stall is the destabilization of the interface between the main and reverse flow [5, 6, 7, 8]. This mechanism can create a larger disturbance in the flow field that blocks flow between multiple vanes. The relative motion of this disturbance with respect to the direction of rotation of the impeller is negative. This phenomenon is called rotating-stall [9]. In the extreme case, a substantial part of the compressor flow cross-section may be blocked and rendered inoperative, which is called deep surge.

Due to the negative effects of stall and surge on the operating parameters as well as the life cycle of compressors and associated process equipment, considerable research attention is being paid to stall prediction, modelling and early warning. The first research works devoted to perturbations formation in the space between the impeller and the diffuser appeared in the 1940s. Since then, several approaches to stall prediction have been developed, such as small perturbation propagation theory, modifications of which still appear in the scientific literature [10], but the method loses validity in the case of a developed rotating-stall. Today, the most widely used method for predicting stall in compressors is based on empirical models [11, 12]. However, these methods are limited by the amount of available experimental data. More recent branches of research in the field of stall prediction are based on the application of chaos theory methods, which make it possible to identify the influence of disturbances on the dynamics of the pressure signal. These methods were first used by Bright [13] and are now successfully applied to experimental data [14, 15] but also to results obtained by numerical simulation [16]. All applications of chaos theory methods are based on the reconstruction of the phase-space from one-dimensional data, resulting in a multidimensional structure called an attractor. By analysing changes in its geometry, it is then possible to identify changes in the dynamics of the source signal due to the presence of minor disturbances preceding more severe manifestations of stall. State-of-the-art stall prediction methods are based on the use of neural networks [17].

Since stall and surge affect the flow field primarily in the space between the impeller and diffuser, it is most advantageous to perform pressure tapping in this area, which requires intervention in the compressor body. However, it also should be possible to use chaos theory to detect changes in the signal dynamics only in the outlet pipe. In the present paper such an analysis will be demonstrated.

2 Experiment and data processing

The experimental circuit (Figures 1, 2) starts with the 400 mm in diameter and 6000 mm long suction pipe fitted with a suction basket. At a distance of 800 mm from the flange, suction static pressure and temperature measurements were made. The discharge pipe was 300 mm in diameter. At a distance of 600 mm from the compressor flange, discharge static pressure and temperature readings were installed. At a distance of 3600 mm from the compressor flange, an anubar probe was installed for flow measurement. Secondary flow measurement was carried out by a nozzle at the end of the discharge pipe. The distance between the orifice and the elbow, which had to be installed on the pipe for space reasons, is 6000 mm, i.e. at a sufficient distance to achieve a stabilized velocity profile.
The parameters that were controlled in the experiment were compressor rotational speed and flow rate. The revolutions were maintained at the desired value by a frequency converter. Once the desired speed was reached, the compressor flow rate was adjusted using a throttle valve. Once the steady state was reached, the averaged quantities needed to determine the operating point of the compressor were recorded. The measurement of the quantities took 25 seconds at a frequency of 10 Hz. Simultaneously with the averaged values, the compressor outlet pressure was recorded at high temporal resolution (25 kHz). In this time recording, the precursors of the incoming stall were further searched for.

![Schematic depiction of the test rig](image)

**Fig. 1.** Schematic depiction of the test rig

The dynamic signal analysis methodology was based on nonlinear feature extraction. In the first step, the phase-space was reconstructed by the time-delay method. In this method, the components of the multidimensional phase-space are formed by parts of the original (measured) signal shifted by the time delay. The choice of two parameters, the time delay and the dimension of the reconstructed phase space, is crucial. Incorrect choice of these parameters can result in the loss of information about the dynamics of the source signal, leading to misinterpretation of the measured data. The result of a correctly performed phase space reconstruction is a structure called an attractor, whose further analysis can extract an indicator of the incoming stall. The parameter that will be used in stall identification is called the correlation dimension. The correlation dimension can be thought of as the slope of the linear part of the correlation integral. In doing so, the correlation integral expresses the number of neighbors in the selected neighborhood of a point on the attractor. Thus, the correlation dimension expresses how the quantity of these neighbors changes as the radius of the neighborhood of the selected point changes.
3 Results

In this section, data measured at constant compressor speed 2350 rpm will be presented. The analyses will consider three regimes, characterized by a dimensionless compressor flow rate $q$, for which $q=1$ at the maximum of the compressor operating curve.

Fig. 3 shows the attractors reconstructed at different operating regimes. At $q = 1.22$, the compressor was operating in a region where stall was not present, while at $q = 0.85$, external stall manifestations such as noise and vibration were clearly observable. As can be seen, qualitatively, a change could be observed on the attractor when stall was reached ($q = 0.85$) however, there were no visible changes on the attractor in the close vicinity of the stall curve ($q = 1.01$). Qualitative change in attractor, which can often indicate changes in signal dynamics, did not work as a stall indicator in this case. However, the attractor can not only be analysed qualitatively, but quantitative parameters can be attributed to it. The dependence of the correlation dimension on the dimensionless compressor flow rate ($q$) is shown in Fig. 4. This quantitative parameter was able to distinguish subtle changes in the dynamics of the measured signal. As the operating point changed towards the stall, the correlation dimension decreased, which means that the signal was less chaotic due to the occurrence of small perturbations preceding the stall, which were deterministic in nature. When stall was not present, the analysed signal was more chaotic, similar to noise, since it was not the result of deterministic processes but of random fluctuations caused by turbulence, thus correlation dimension was larger.

Fig. 3. Attractors reconstructed from the outlet pressure dynamic signal, embedded dimension = 3, nshaft speed = 2350 rpm


4 Discussion

The article is dealing with the issue of stall in centrifugal compressors. Regardless of the origin or type of stall, the compressor in this operating condition is subject to flow field disturbances in the tip clearance and the impeller and diffuser interstices. The resulting perturbations deflect the gas stream thereby reducing the effective flow area and reducing the compressor output parameters. In addition, these disturbances are dynamic in nature, moving or periodically appearing and disappearing. This influence the dynamic waveform of the output pressure. The effect of stall on tip clearance pressure is quite significant and well analysable. As the gas being pumped gets further into discharge, pressure attenuation of the weaker pulsations occurs, down to the level of signal noise. Therefore, detection of small disturbances that precede stall at the compressor outlet is difficult until the stall begins to manifest itself in noise and vibration. At that point, the attractors’ shape changes. Using phase space reconstruction, however, it is possible to detect the influence of the weak stall precursors on the signal dynamics. The advantage of the present method is that there is no need to interfere with the compressor design, but the pressure signal can be acquired at a more accessible location, such as the outlet pipe.

Fig. 4. Calculated fractal dimension for stall and non-stall conditions

References

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