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Non-stationary processes in a centrifugal compressor: from experiment to practice

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Abstract. The article deals with the problems of diagnostics of surging phenomena in centrifugal compressors. The reasons for the surge phenomenon and the method for its diagnosis to prevent emergencies are stated. The article describes the phenomenon of rotating stall, which precedes the surge. Diagnostics of the appearance of a rotating stall opens the possibility of predicting the appearance of a surge. This allows for an efficient and safe surge protection system. Solving the problem of developing new principles for constructing surge diagnostics systems. Application of biorthogonal wavelet transform for prebreak detection.

Key words: virtual stand, unsteady processes, centrifugal compressor, Ansys, rotating breakaway, aerodynamic, three-dimensional.

1 Introduction

In the early stages of development, unsteady processes in turbochargers were considered as a kind of curiosity accompanying the functioning of the system. The only non-stationary process that everyone knew about was surge. At the same time, the theory and practice of the study of surge have been developed little. Before the First World War, N.Ye. Zhukovsky presented a report [1], which describes a phenomenon that today can be interpreted as a rotating stall. However, the scientific and technical community practically did not notice this part of the work. In the 30s in Germany, K. Fischer [2] and E. Grünagel [3] in their works on the study of pumps, cited in almost every textbook on turbomachines, described a phenomenon that can be interpreted as a rotating stall (Fig. 1), and even presented an attempt to describe these phenomena in terms of potential flow.

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Fig. 1. Phases of rotary stall in a centrifugal pump [2, 3]

The explosion of work on the study of rotary stall in axial compressors, observed after the work of Emmons, Pearson and Grant [4], practically did not affect centrifugal compressors. Only the study of an insulated bladeless diffuser, carried out by V. Jansen [5], revived interest in rotating stall.

Abroad, research on rotary stall in centrifugal compressors was initiated by the disaster in the North Sea on a high-pressure compressor, which led to gigantic environmental pollution. [6, 7]. It turned out that the rotating stall created the so-called asynchronous (non-multiple to the rotor speed) oscillations. Since all these effects manifested themselves in industrial installations, almost the overwhelming majority of studies were carried out with vibration measurements, which did not allow revealing the physics of the process - aerodynamic in nature.

2 Methods

The university laboratories, despite the natural limitations of a financial and technical nature, have managed to significantly advance the research of nonstationary processes such as rotating. Here, the help of industry played an important role - in our case, G.A. Raer (NZL), who initiated research to determine unsteady aerodynamic loads that cause vibrations of the impeller disks. This led us to develop a method for measuring these loads in rotating wheels. Of all the variety of methods for measuring non-stationary pressures, it was necessary to stop at the use of strain gauge pressure sensors (small-sized, suitable for setting in rather thin disks of impellers) and mercury

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current collectors for communication with stationary equipment. With practically no experience (and finances), we were forced to create a line of small-sized semiconductor pressure sensors (Fig. 2), which provide a high signal-to-noise ratio and are suitable for studying almost all types of non-stationary processes. At the next stage, we (with the help of G.V. Smirnov, associate professor of the Department of Hydroaerodynamics of the LPI) managed to create hot-wire anemometers, which made it possible to measure unsteady velocities. Since the amount of information received was huge, we managed to solve the problem of automating the processing of experimental data using the experience and equipment of a nuclear physics experiment [8].



Fig. 2. Low-response pressure sensors (a) for impellers, b) for diffusers [8]

3 Results and Discussions

For experiments, it was necessary to modernize the existing stands. The first such stand - ETSK-1 (Fig. 3) of the laboratory of compressor construction LPI turned out to be a rather convenient object, since it made it possible to relatively easily change the configuration of the flow path. High-speed mercury current collector developed by the plant. Klimov was installed in a split pipe at the suction, in the case of stands at the NZL and at the CKTI, the drive circuit with a multiplier made it possible to place the current collector on the console. Up to 16 sensors were installed in the impellers. In stationary elements, pressure sensors and hot-wire anemometers were installed.



Fig. 3. Stand ETSK-1M of the laboratory of compressor construction LPI [8].

The specificity of the study of rotating stall is the need to use at least two sensors on the same diameter, displaced by a certain angle (not a multiple of 2π), since the separation zones move with an angular velocity that differs from the rotor speed. The use of meters on the rotor and stator makes it possible to simplify the task of determining the number of zones and the speed of movement of the stall zones.

For illustration, Fig. 4 shows a summary picture of unsteady processes in a stage with a two-tier impeller $\beta l2 = 90^{\circ}$ and a bladeless diffuser (stand ETSK-1M).

The complexity of the observed processes is evident; rotating stall occurs at flow rates less than optimal. A study in the same flow path with impellers $\beta l2 = 21$, 49, 63 and 90 ° and bladeless and vane diffusers showed that rotating stall is a phenomenon generated by separation on the diffuser walls at flow angles at the diffuser inlet $\alpha 2 \leq 12 \dots 16^\circ$. (The upper value corresponds to high Mc2 numbers). The relative speed of rotation of the stall zones is low (less than 0.1).



Fig. 4. Summary picture of non-stationary processes of the river to. $\beta l2 = 90^{\circ} + vls [8]$.

The use of hot-wire anemometers made it possible to obtain a clear picture of the formation of a rotating stall in the diffuser, since it is the diffuser (both vane and vaneless) that initiates the three-dimensional separation, which generates a rotating stall. In fig. 5 shows "frozen" patterns of velocity and pressure fluctuations in a vaneless diffuser obtained by synchronous accumulation. The shaded areas correspond to the return flow zones. The three-dimensional nature of the flow is illustrated in Fig. 5; it is clearly seen that the stall is most intense near the walls of the diffuser [8, 9]



Fig. 5. Pulsations of speed at rotating stall in the stage of r.c. $\beta l2 = 49^{\circ} + vls.d.$ [8, 9].

The actual rotating stall, which usually occurs near the surging boundary, is preceded by a phenomenon called a "precursor stall". This phenomenon was discovered by us during tests of stages with blade diffusers on the bench of the K350 NZL compressor [8]. A characteristic feature of this process, which we called "standing stall," is a local separation on the walls of the diffuser, which practically does not move along the circumferential coordinate. Measurements on the impeller make it possible to clearly detect this process, since the arising pulsations are multiples of the rotation frequency (in this case, low-frequency pulsations are observed in the diffuser, the period of which is much longer than the period of the rotating stall).

It was with the study of prebreakdown that the practical use of the results of the study of non-stationary processes began. This is due to the problem of building an anti-surge protection system. The existing protection systems are divided into two groups: parametric (measuring, for example, the flow rate by the pressure drop across the diaphragm, and triggered when the "setpoint" is reached - a line shifted relative to the surging boundary, determined organoleptically) and indicative, built on determining the effects preceding the onset of surge [10].

In fig. 6 shows a typical compressor performance with event limits. Since flow or pressure meters introduce uncertainty, which is the smallest at the maximum value of the measured value, and rather large precisely in the area of measuring low flow rates corresponding to surge, the ambiguity in determining the "setpoint" can lead to the compressor getting into surge (cases have been noted in the practice of operating natural gas blowers, when the pulsations in the flow measurement system exceeded the permissible level of error in flow measurement). Feature systems are built on the registration of the occurrence of a phenomenon preceding the surge. Such a phenomenon is a rotating stall that occurs before surge, which is quite easily identified by modern methods. It should be noted a characteristic feature of natural

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gas blowers developed by NZL, in which a rotating stall occurs in the immediate vicinity of the surge. In this case, the detection of a pre-break allows you to build a reliable surge protection.



Fig. 6. Compressor characteristics and characteristic areas of operation.

This is a typical detection problem solved in any radio-technical target detection system, with appropriate restrictions on the likelihood of missing a target (rotating stall not detected) or false detection (rotating stall occurs far from the surging boundary). In general, these problems belong to the modern problems of information theory.

From our previous experiments, the main characteristics of the rotating stall (frequency, number of stall zones, relative speed of movement) were known. An experienced experimenter, observing the results of measuring the pressure and velocity pulsations on the screens of oscilloscopes, diagnoses the moment of occurrence of a rotating stall with a high degree of reliability. However, for industrial applications, it was required to solve this problem in real time automatically, while strict restrictions were imposed on the delay in decision making (no more than 1 ... 5 seconds) in order to prevent the compressor from hitting a surge and to provide a margin of time for opening the anti-surge valve.

Practice made us study rotational stall not from a physical point of view, but from a detection point of view. It was here that quite serious problems arose in the field of mathematical physics and information theory. One of the main tasks of analyzing a stochastic process is to determine the period of fluctuations. For a sinusoid, this procedure seems trivial. However, even AA Kharkevich [6] showed that the true period of such a "primary" process with traditional hardware detection using the Fourier transform is formed with an infinite observation time. The observation time during the experiment is always finite. The task becomes much more complicated due to the non-stationarity of the process inherent in any system, especially a centrifugal compressor. Hence the problem of determining (revealing) the latent periodicity arises. In the scientific literature [6, 11, 12] this problem is considered from the classical point of view. We needed a practically usable solution. The computer implementation of the method was of no small importance.

At the first stage, a windowed transformation was applied to obtain current estimates of the autocorrelation function using the Lanczos weight function. This made it possible to obtain a satisfactory selectivity even for pulsations in the prestart mode, in which characteristic periodic oscillations are observed over a short time interval. Later, short-term correlation analysis was successfully applied to solve the problem of detecting both rotating stall and pre-stall [10, 13]. All calculations were carried out in the Matlab environment using personal computers (Fig. 7). Impressive results were obtained using the Hilbert transform (Fig. 7-c, d).



Fig. 7. Processing of oscillograms of pulsations during rotating stall (a) using short-term correlation functions (b) and Hilbert transform (c, d) [14].

Conclusions

The development of the obtained results occurred in the works of Nguyen Minh-Hai, who applied singular spectral analysis (SSA) to solve the same problem [15, 16]. The advantages of this method are not only higher selectivity, but also the possibility of recovering the converted (noise-free) signal in the time domain, which makes it possible in the future to successfully apply traditional spectral methods.

The next step on the way of detecting rotating stall and pre-stall was made by A.A. Lebedev [17, 18]. He successfully applied wavelet transform to solve the problem. The task was not easy, because he managed to select from the whole variety [19] the so-called biorthogonal wavelet, which made it possible to solve both the detection problem and the problem of signal recovery with a very high level of noise immunity (Fig. 8).



Fig. 8. Application of biorthogonal wavelet transform (left) to detect prebreakdown (right) [18]

Thus, the problem of developing new principles for constructing surge diagnostics systems was solved. Note that the principles of building the system are protected by Russian patents. The main ideas were confirmed by our field experiment on a natural gas blower 395-21-1 (Neva-16 unit) at the Rzhevskaya compressor station.

Nowadays CFD methods are becoming very important. Using CFD methods on a supercomputer, the characteristics of turbochargers are calculated [20-22]. This allows you to study in detail the surge phenomenon and build an effective system for its diagnosis [23-25].

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