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Development of a Surge Prediction System for Multi Stage Axial Compressors

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ABSTRACT

Measurement results from different multi stage gas turbine compressors for the investigation of periodic pressure fluctuations with respect to changes due to increasing aerodynamic load. By analyzing the signal patterns of dynamic pressure transducers mounted above the first rotor with different methods suitable parameters could be defined which indicate the approach to the compressor stability limit.

Based on these results a monitoring algorithm for the prediction of unstable compressor operation was developed. By means of appropriate correction method the system could be optimized so that various influences, for example different operating conditions, geometry and ambient conditions, can be neglected.

The system was applied to three different gas turbine compressors as well as to a research compressor without any changes of the parameters. In each case a warning was triggered off before unstable operation occurred.

NOMENCLATURE

FFT	Fast Fourier Transformation
m	root order for geometry correction
max	maximum
min	minimum
n	rotor speed
p	pressure
ref.	reference
rev.	revolution
RMS	root mean square

INTRODUCTION

As a component of a gas turbine the compressor has a severe influence on the efficiency of the entire machine. With respect to a reduced consumption of primary energy as well as a reduction of green house gases it becomes more and more important to establish operating points on a higher efficiency level than today. One major aim of future compressor designs has to be an increase of the aerodynamic load with operating points close to the stability limit. It is state of the art to define the compressor operating points in a sufficient distance from the stability limit in order to avoid unstable operation. However, increasing aerodynamic loads lead directly to a reduction of this safety margin. In order to guarantee stable compressor operation even for these high load conditions a permanent monitoring of the aerodynamic load and a reliable warning mechanism for the a approach to the surge line becomes necessary.

During the last years an increasing number of investigations is dedicated to stall and surge detection and prediction. (Bright et al. 1996, Day et. al. 1997, Methling et al. 2002). Different attempts were made to analyze the flow phenomena and to define suitable and reliable detection methods. One major aim for the future is to use the detection results as a basis for a system for active stall control in axial compressors.

In order to provide sufficient reaction time such a prediction system has to detect the approach to the stability limit early enough and reliable. This issue is important especially for full speed operating points. Various investigations show that at these conditions a significant hysteresis exists between onset and disappearance of unstable compressor operation. In many cases a shut down and restart of the machine is necessary to leave the unstable operating range. Therefore, the method described in this paper was developed with respect to an on-line analysis and an integration in a gas turbine control system.

EXPERIMENTAL INVESTIGATIONS

Detailed experimental investigations were performed at different gas turbines on the test field of Siemens Power Generation in Berlin. The compressors were equipped with dynamic pressure transducers in various stages (Fig. 1). In a first step in the stages one and two several sensors were mounted in the casing above the rotors in order to get an impression of the fluctuations inside the rotor passages. In addition in the stages 8, 11 and 15 one wall mounted sensor at 50 % rotor chord length showed the unsteady pressure distributions.

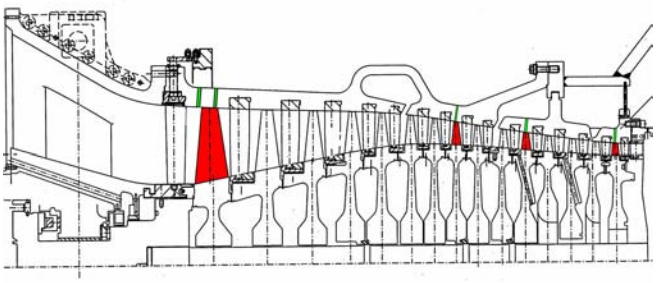

Fig. 1: Measurement locations in the compressor

The signals should provide information on the possibility of detecting the approach to the stability limit by changes in the signal patterns. In addition the most suitable measurement position in the compressor should be found. Therefore, a test run schedule has been defined covering different operating conditions. The aim of all these tests was to reach the stability limit at different boundary conditions (speed, load, vane setting). Two different kinds of tests were performed. First the gas turbine was forced into surge by reducing the rotor speed from nominal operation down to surge. In

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a second phase at full speed the stability limit should be reached by fuel spiking. The results showed that the most reliable and suitable information could be obtained from a sensor in the first stage. As a result from a comparison of the signal distributions of all investigated machines the optimum position could be found in the range between 30 % and 50 % chord length.

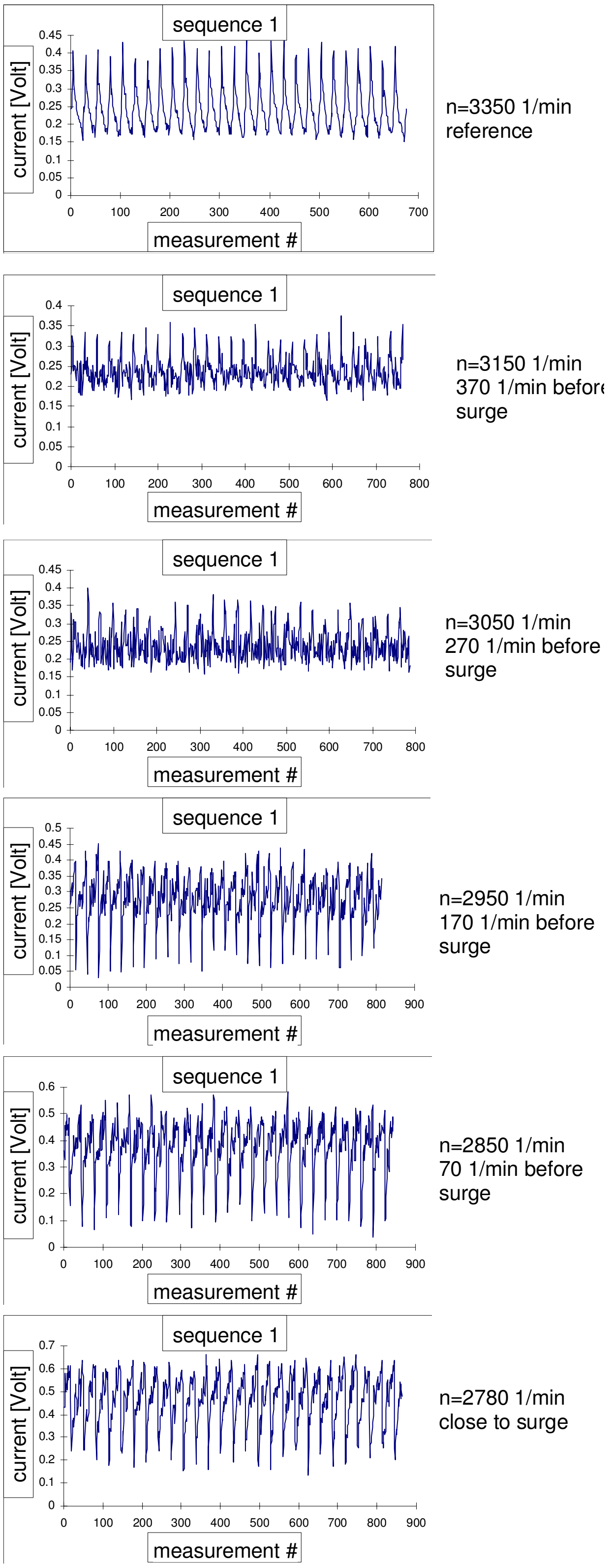

Fig. 2: Changes of pressure fluctuations due to increasing compressor load

The real time signals of a sensor at that location demonstrate the significant change of the patterns with increasing compressor load (Fig. 2). The measurements were taken at a test run with speed reduction down to surge. Each of the diagrams depicts the pressure fluctuations measured at a defined compressor operating point (RPM before surge).

In sequence 1 each blade passing can be identified by a defined pressure peak. The region between two peaks shows the pressure distribution inside one rotor blade passage. Following the signal structure from right to left after the peak of the rotor blade a sharp pressure drop occurs. This minimum characterizes the blade suction side. Then a pressure rise towards the pressure side of the next blade can be observed before the next peak is caused by the blade tip passing the sensor.

With increasing aerodynamic load these clearly visible process becomes influenced by other effects. First the peak amplitudes decrease and the pressure distribution in the passage becomes disturbed. Then these disturbances also superpose the pressure peaks and the blade passing region in the signal patterns is enlarged. Finally the pressure fluctuations are totally influenced by flow effects in the radial gap between blade tip and casing. The blade passage can only be detected as a short pressure drop.

This process can be explained by flow effects in the tip gap. Wang et al (2002), Saathof et al. (2002) and Wernert et al. (2002) showed that the position of the tip leakage vortex depends on the aerodynamic load. With increasing load the vortex is shifted upstream. Due to this behavior the pressure distributions measured by the transducer located above the rotor becomes more and more influenced by the vortex flow.

ANALYSIS OF THE MEASUREMENT RESULTS

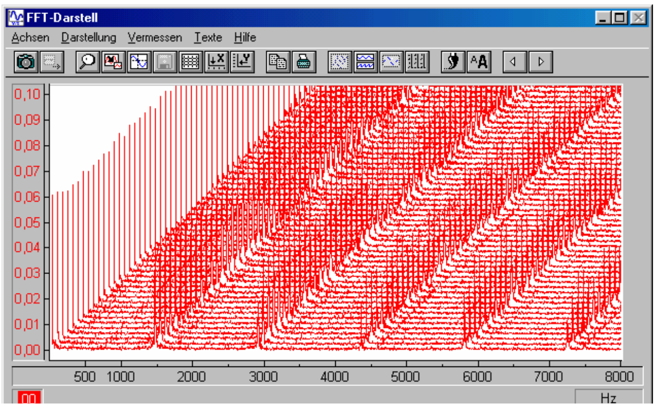

Fig. 3: FFT Waterfall diagram for nominal operation

Since all investigated compressors showed the same behavior of unsteady pressure distributions a detailed analysis of the real time signals should give an impression about the dependencies and interactions. In a first step an FFT analysis was performed. Fig. 3 shows a waterfall diagram representing nominal compressor operation. The peaks for rotor blade frequency and the harmonics are clearly visible.

Close to surge the spectra show a significant change (fig. 4). The amplitudes at blade passing frequency become reduces and additional smaller peaks occur. The surge event (middle of the picture is characterized by missing periodic information and strong disturbances especially in the lower frequency range directly after the event.

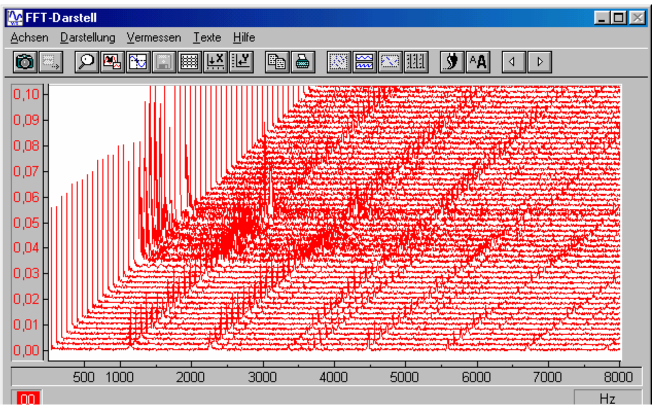

Fig. 4: Waterfall diagram for operation around surge

Various analysis methods were applied in order to obtain relevant information from the real time signals. Based on the results appropriate parameters for the surge prediction should be defined. The main issue of this task was to detect and to eliminate effects caused by different reasons that could influence and disturb the signal behavior. Therefore, the following parameters were calculated from the real time signals.

- Mean value of the FFT signal
- RMS value of the FFT signal
- Dispersion
- Average value over the first 10 peaks (rotor blade frequency)
- RMS value over the first 10 peaks (rotor blade frequency)

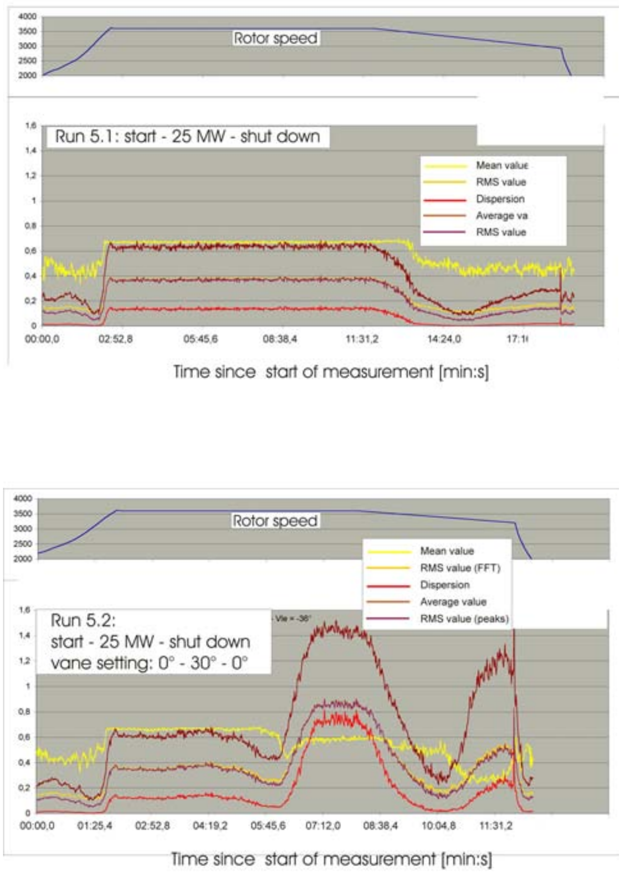

Fig. 5: Comparison of various statistical parameters
Top: influence of rotor speed
Bottom: influence of vane setting

Figure 5 shows a comparison of these parameters for two different test runs of the V84.3 gas turbine. In the upper part of both diagrams the rotor speed demonstrates the test procedure. Starting at nominal speed of 3,600 1/min after a while the speed is slowly reduced until surge occurs and the machine is shut down. The diagram at the top makes clearly visible how the different parameters are influenced by the speed reduction. No defined trend with approach to the stability limit can be observed. In the bottom diagram the parameter distributions are influenced by changing the vane setting. Both example demonstrate that these parameters are no suitable for a surge detection. However, they can be used to eliminate possible influences of different effects on the monitoring results.

In order to define appropriate monitoring parameters for the aerodynamic load and the approach to the stability limit further analyses were focussed on the frequency spectra. Based on the observations in the waterfall diagrams detailed parameter studies were performed.

DEFINITION OF SURGE DETECTION PARAMETRERS

The most promising way to define parameters that depict all the effects occurring during the increase of compressor load up to the stability limit was to take into account the behavior of the different frequency peaks. On one side the amplitudes at blade passing frequency become reduced, on the other side new frequency peaks occur and grow until the stability limit is reached.

A first step was to sum up the amplitudes of the rotor blade harmonics in a defined range of the spectrum in order to cover the effect decreasing periodic information. Since the spectra also are influenced by the new small peaks growing close to surge a special technique had to be applied to the further analyses. By signal selection the regions between the harmonics were blanked out so that only the remaining amplitudes (blade harmonics) could be summed up so that the so called signal form parameter could be calculated.

This parameter aims on the changes of the rotor blade harmonics close to surge. It provides a suitable basis for the detection of the stability limit. In comparison with the statistically derived parameters shown in figure 5 the behavior is much more concentrated on the real flow effects due to increasing aerodynamic load than on changes due rotor speed or vane variations.

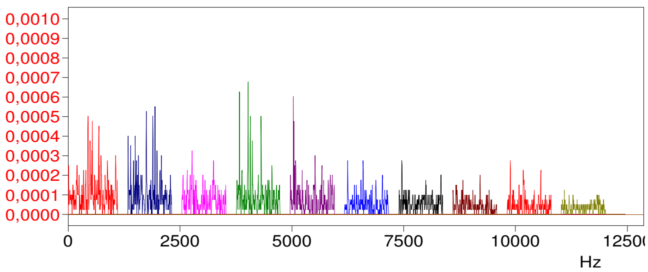

Fig. 6: Signal selection (rotor blade harmonics blanked out)

As already described above with approach to the stability limit new small peaks appear in the frequency spectra. They cannot be located at defined frequencies due to rotor blade numbers or other countable periodic effects. Therefore, the evaluation of these additional peaks only could be carried out by an overall method. Similar to the signal treatment for the calculation of the form parameter a signal selection became necessary. The main difference is that in this case the harmonics were blanked out from the spectra (fig. 6). By means of numerical differentiation, building the absolute value and finally integration the stability parameter is calculated from the remaining signal.

By this procedure already small frequency peaks can be taken into account. As a disadvantage the high noise level must be addressed, which influences the absolute value significantly. However, it was found that the noise remains nearly constant with increasing load and can be treated as a signal offset. Nevertheless, some speed and geometry influences on the signal behavior could be observed.

The speed sensitivity is caused by the kind of signal selection. With speed reduction the rotor speed harmonics are shifted to lower frequencies and the regions in between become smaller. Thus, the number frequency peaks to be summed up is reduced which leads to a distortion of the parameter trend. By the definition of a suitable correction factor the effect can be eliminated.

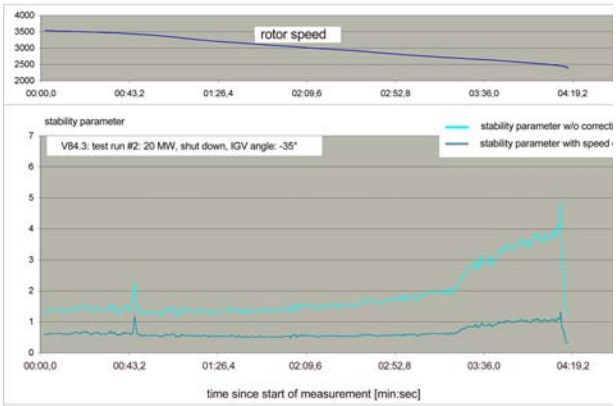

Fig. 7: Stability parameter with and without speed correction (top: rotor speed, bottom: stability parameter, upper curve w/o speed correction, lower curve with speed correction)

Figure 7 shows the comparison of the parameter trend with and without speed correction. The diagram shows a time period of about 4 minutes covering the speed reduction from 3600 1/min down to 2450 1/min where the surge occurs. Even from the speed corrected parameter distribution (lower curve in the bottom diagram) the increase close to the stability limit becomes visible. This behavior could be observed for test runs. Nevertheless, the parameter is influenced by other effects so that the definition had to be improved.

In a second step the geometry dependency had to be eliminated by using an appropriate correction method. Therefore, a detailed analysis of the parameter behavior at different vane settings was performed. Based on the results a parameter could be defined by empirical methods that is only influenced by geometry effects. Unfortunately the behavior with increasing compressor load was slightly different from that of the stability parameter so that a weighing function had to be applied. A root function turned out to be most applicable. Figure 8 demonstrates the effects of the geometry correction. The different curves characterize different root orders m. The increasing aerodynamic load of the compressor due the reduction of rotor speed is perfectly depicted by the trends of all curves. The vertical line at the right side of the diagram characterizes the stability limit.

The aim of the definition of that correction process was to find that root which fits for all test runs and provides similar trends of the stability level. A root order of m=3 matches these criteria. This configuration shows the best compromise between gradient of the curve and disturbances due to noise effects.

The main issue for safe surge detection is a proper definition of criteria for an instability warning. This contains both, the estimation of a suitable reference condition to define stable resp. nominal operation as well as the estimation of a critical level or range which indicates the approach to the stability limit. These should be based on the following requirements

- similar behavior for all operating conditions
- easy to calculate form the measurement data
- independent from the performance map of the compressor
- independent from the compressor geometry and design

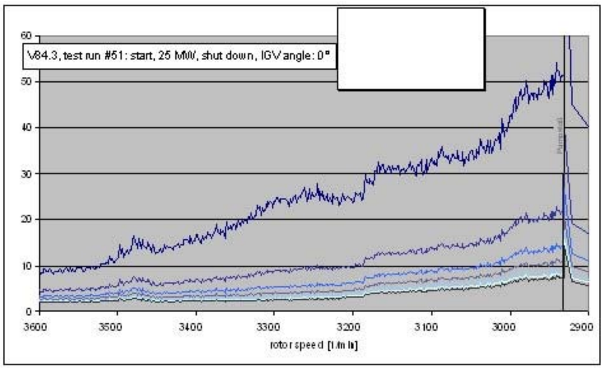

Fig. 8: Stability parameter with speed and geometry correction

By relating the stability parameter to the form parameter described above these requirements could be met. The reference level is calculated from the signals values at nominal compressor operation. The analysis of the parameter trends derived form the different test runs showed that with the above combination a reliable surge detection becomes possible. On the basis of the available test run data the warning criteria could be defined as exceeding twice the reference level (1st warning) resp. 3 times the reference level (2nd warning).

PARAMETER BEHAVIOR

After having optimized the parameters as described before the algorithms were tested applying them to the different test runs of the gas turbines and in addition to measurement data of two research compressors. A comparison of the results should give an impression of the reliability of the monitoring procedure.

Figure 9 shows the behavior of the stability parameter for one test run of a V84.3A gas turbine. The lower part demonstrates the distribution of the stability parameter, whereas in the upper part the rotor speed is shown. The vertical line at the right side marks the stability limit. From the intersection of this line with the speed curve the dark horizontal line in the upper diagram shows that the stability limit is exceeded at 3150 1/min.

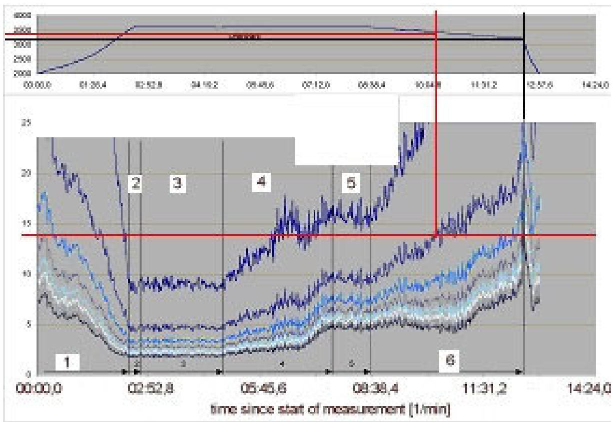

Fig. 9: Behavior of the stability parameter for a test run with changing the vane setting

The ranges of different operating conditions are marked in the diagram by numbers. In order to verify the appropriate choice of the root order all investigated settings are included in the diagram.

The following operation conditions can be observed:

1 Start of the gas turbine
2 Set load to 25 MW
3 Stable operation at 25 MW
4 Close guide vanes
5 Stable operation with closed guide vanes
6 Speed reduction until surge occurs

This figure shows the same test run as described in figure 5 (bottom). Whereas the statistical parameters in figure 5 are highly influenced by the change of the vane setting (region 4 in fig. 8) the stability parameter only shows a slight increase in that range. As described before a root order of 3 was found to provide the best results for all cases. Therefore, the following analysis shall be focussed on the regarding curve (second from top).

The reference level at nominal operation can be derived from the diagram as approximately 4.8. With respect to the definition of the surge warning level (twice the reference level resp. three times the reference level) these values are calculated to 9.6 (1st warning) and 14.4 (2nd warning). The first warning is given directly after the begin of speed reduction. The second warning (characterized by the red horizontal line in the lower diagram) is exceeded at about 200 1/min before the surge speed. Even the influence of closing the guide vanes will provoke no operational failures.

As a comparison another test run with constant vane setting shall demonstrate the reliability of the detection results (fig. 10). The different operation ranges are as follows:

1 Start
2 Stable operation (no load)
3 Increase load to 25 MW
4 Stable operation at 25 MW
5 Speed reduction until surge occurs

In this case the rotor speed at the stability limit was found to 2970 1/min and the warning was generated at approx. 3150 1/min which is 120 1/min in advance. That means that the surge warning for both test runs appeared at the same load level and is independent from the vane setting and other influences.

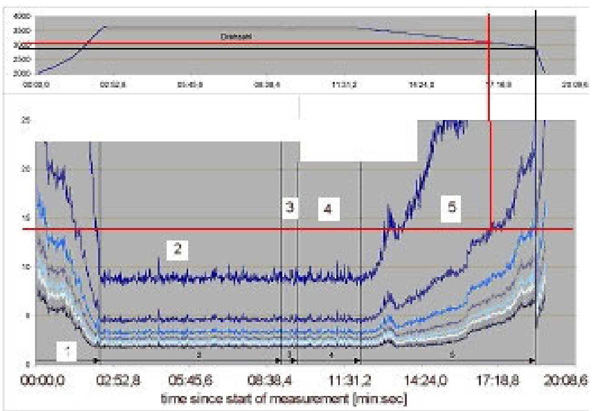

Fig. 10: Stability parameter for one test run with fixed vane setting

All the investigations described above were based on measurement data that were derived from test runs with the Siemens gas turbines. A remarkable disadvantage of all these test data is that they only demonstrate the pressure fluctuations at part speed operation. In all cases the stability limit was reached by speed reduction down to approx. 80%– 85%. Additional test runs with fuel spiking were not successful. At 100% speed in no case the compressor could be forced to surge.

Therefore, the verification of the parameter behavior demonstrated in the figures 8 and 9 can only be a first check of the reliability of the method. As already mentioned above the part speed case is not characteristic for a real gas turbine operation. It has to be proved whether a sensor which is mounted in the first stage would also produce appropriate information for a 100 % case. On the other hand the time from nominal operation until occurrence of surge was quite long. That means the change of the operating conditions of the compressor was done very slowly. In reality this gradient would be much higher.

In order to get an impression of the parameter behavior at 100 % speed the above method had to be applied to additional measurement data. At the University of Hannover detailed investigations at a four stage research compressor were performed. The compressor design is totally different from the gas turbine compressors and the design rotor speed is with 17,000 1/min significantly higher. During the test series the compressor was operated at different speed from 50% up to 100%. The compressor was throttled down to an operating point near the stability limit. Then by an abrupt closing of the throttling device instability was generated. Thus, additional data for the verification of the surge detection algorithms were available.

As an example figure 11 demonstrates the behavior of the stability parameter at a 100 % speed test run. For comparison with the diagrams before also the different orders for the correction roots are included.

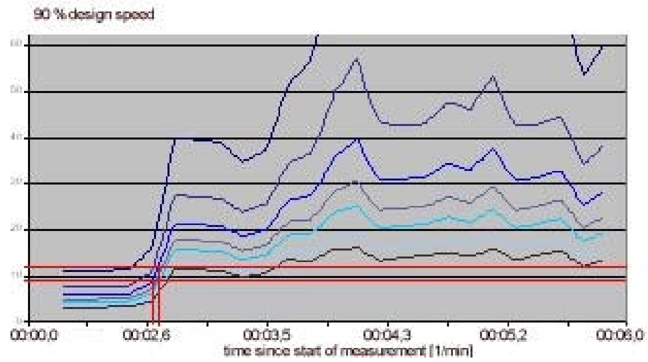

Fig. 11: Analysis of the Hannover compressor

After the start of the measurement a short period of constant operation close to the stability limit can be observed. Then within very short time the throttling device is closed and the compressor falls into Rotating Stall. During the first phase the stability parameter keeps nearly constant. With increasing load it jumps up very quickly. A detailed analysis of this process shows, that a warning was provided before the stability limit. The whole procedure can be described by the following steps.

- reference level: 4.2 (derived form a stable operating point at 100 % speed)
- after 2.66 seconds from the start of the measurement the 1st warning level is exceeded (horizontal red line)
- after 2.72 s from the start of the measurement the 2nd warning level is exceeded (upper horizontal red line)
- after 2.82 s from the start of the measurement Rotating Stall occurs (first maximum of the curves)

That means that the first warning was generated 150 ms (43 revs.) before stall and the second warning was generated 90 ms (26 revs.) before stall. The example shown here is the worst case that was analyzed. For all other test runs the time periods between warning and instability were much longer.

This verification shows that the method developed on the basis of measurement data from multi stage gas turbine compressors is applicable also to other machine types without any changes of the parameter definition or the calculation scheme for the warning criteria. In addition it could be demonstrated that it is not only valid for part speed operation but also for 100 % speed.

CONCLUSIONS

Based on measurement data from various gas turbine compressors a system for surge and instability detection in multi stage axial compressors could be developed. By means of different analysis methods suitable parameters and algorithms were defined which only depend on the aerodynamic load of the compressor.

The system was applied to measurement data derived from various test runs in order to verify the reliability and the universal validity of the algorithms. The results demonstrated that even for compressors with different designs and stage numbers a surge detection is possible in all cases. Since appropriate correction parameters could be found the estimation the regarding warning levels is performed automatically during nominal operation.

This method can be used as a basis for the development of an on-line monitoring system for surge and stall detection in multi stage axial compressors.

ACKNOWLEDGEMENT

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REFERENCES

Bright, M.M., Qammar, H.K., Weigl, H.J., Paduano, J.D.
“Stall Precursor Identification in High Speed Compressor Stages Using Chaotic Time Series Analysis Methods”
Proceedings of the ASME Turbo Expo 1996, Paper No. 96-GT-370

Day, I., Breuer, T., Escuret, J., Cherrett, M., Wilson, A.
“Stall Inception and the Prospects for Active Control in Four High Speed Compressors”
Proceedings of the ASME Turbo Expo 1997, Paper No. 97-GT-281

Methling, G., D´Stoff, H., Grauer, F.
“The Pre-Stall Behavior of a 4-stage Compressor and Stall Monitoring Based on Artificial Neural Networks”
Proceedings of the 9th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery 2002, Honolulu, Paper No. FD-ABS-017

Wang Songtao, Wang Zhongqi
“The Tip and Hub Leakage Flow of a Repeated Two Stage Compressor“
Proceedings of the ASME Turbo Expo 2002, Amsterdam, Paper No. GT 2002-30437

Wernert, M.P., Van Zante, D., Strazisar, T.J., John, W.T., Prahast, P.S.
“3-D Digital PIV Measurements of the Tip Clearance Flow in an Axial Compressor”
Proceedings of the ASME Turbo Expo 2002, Amsterdam, Paper No. GT 2002-30643

Saathoff, H., Deppe, A., Stark, U., Rhodenberg, M., Rohkamm, H., Wulff, D. und Kosyna, G.
“Steady and Unsteady Casingwall Flow Phenomena in a Single-Stage Low-Speed Compressor at Part-Load Conditions“
Proceedings of the 9th International Symposium on Transport Phenomena and Dynamics of Rotating Machinery 2002, Honolulu, Paper No. FD-ABS-038