**REPÜLÉSTUDOMÁNYI KÖZLEMÉNYEK**
35. évfolyam (2023) 3. szám 103–116. • DOI: 10.32560/rk.2023.3.7

Zsolt István Faltin, Károly Tamás Beneda

# Improvement of a Centrifugal Compressor Test Bench to Incorporate Variable Impeller-Inducer Bleed Air System as an Active Surge Control

*Centrifugal compressors are widely used throughout various industrial applications, including many safety-critical fields like aircraft engines. Thus, the enhancement of stable operational range is essential, which often requires active surge control methods. This includes state-of-the-art digital electronic measurement system to detect the onset of surge, which is a phenomenon that arises under extreme operational conditions and can lead to either negatively influenced behaviour or even the destruction of the compressor hardware in the case of uncontrolled conditions. Therefore, a strong emphasis must be given to observe impending surge and, if possible, to include an active system that can prevent undesired operational situations. Amongst many passive and active possibilities of surge control, Blade Load Distribution Control (BLDC) can be considered as a method, which creates acceptable influence on instabilities with a minor efficiency loss, consequently, could be applied as an active surge suppression system. The aim of this paper is to investigate feasible solutions on an existing centrifugal compressor test bench, which would enable to examine the theoretical solutions for blade load distribution control.*

**Keywords:** *centrifugal compressor, compression system instabilities, surge suppression methods, bleed air, blade load distribution control*

## 1. Introduction

In the aerospace industry, centrifugal compressors are used especially in the propulsion systems like as high bypass turbofan (e.g. Lycoming ALF502), turboprop (e.g. Pratt & Whitney Canada PW100) and turboshaft (e.g. Klimov GTD-350) engines. Turbofan and turboprop engines are intended for airliners and medium sized, general-purpose aircrafts to generate thrust. Turboshaft engines combined [1] with reduction gear system are the main power generation system of helicopters (e.g. Mil Mi-2). The surge phenomenon could occur in both applications when operational conditions change suddenly, for example during take-offs and landings or in unpredictable situations, for example at bird strike event, which could cause fatal failure of the engine in any phase of the flight, for example in PW100 series engine family. The advanced version of this engine, the PW150 applies a 3-stage axial compressor replacing the first, low-pressure centrifugal compressor in the PW100, or the so called Jet-Net equipment can be used to protect the engine inlet section against entering foreign objects like at MTR390 or at Jet Cat P100 micro gas turbines. When input parameters change immediately, compressor stall could occur, and this could cause pressure oscillations, which could propagate towards the combustion chamber. If the amount of air is insufficient in the combustion chamber and only a portion of the fuel participates in the combustion process, these conditions, when not controlled, can lead to complete failure of the engine. That is why the theoretical and experimental examination of the surge phenomenon [2] and investigation of effective solution methods is of emphasised importance today.

### *1.1. The surge phenomenon*

The research of the dynamic behaviour of instabilities in compression systems has had major role in many fields of industrial applications for decades [3], [4], [5], especially in aerospace and energy sector. These researches [12] focused on multitude of aspects of the phenomenon from its emergence and mechanism [13], [14], [15] through its features in a specified environment [16] to its elimination in an existing system like a compressor stage of a turbocharger, but only a few paid attention for the detection and active controlling of the compressor surge [17], [18]. These researches help to understand the phenomenon and grant support for further developments.

In a numerical investigation [6], the authors have created the exact 3D model of an existing centrifugal compressor (NASA CC3). They conducted an unsteady three-dimensional numerical simulation based on large eddy simulation (LES). One of their conclusions was that a surge event could be divided into five stages. The first is the *pre-surge interval,* which started when the backpressure of the flow has started to increase and flow separations were observed on the diffuser vane walls and corner separated flow developed near the hub corner just downstream of the leading edge of the vane. After that, the phase of *surge inception* was defined. It was caused by the large increase in the static pressure in the diffuser channels in where some fluctuations were observed in the rotating stall cells. In the *flow reversal interval,* recirculation flow was formed in the diffuser passages. This backflow was generated by the adverse pressure at the diffuser outlet. The next in the *recovery flow inception phase,* where the flow reattached to the normal direction, because the backpressure which caused this backflow started to decrease. The *reattachment phase* is that shows the continuation of the flow recovery. In this segment of surge, pressure started to increase close to the stable operating value before the compressor will enter to the next surge cycle. The better understanding of a surge event helps to determine the appropriate detection and control method of the phenomenon.

Another study [7] has investigated the surge from other aspect. A real turbocharger centrifugal compressor equipped with a vaned diffuser was examined at five different rotating speeds. The experimental results have shown that the transitional process from stable to unstable condition is different at these dissimilar circumstances. At low rotating speed, the transition process consists of two segments, like *the stable operation and the deep surge stages,* while at high rotating speed, the transition process includes one more segment between the stable operation and the deep surge cycle. It is the *mild surge,* which has occurred only at the highest rotating speed (90,000 1/min) in the experiment. The difference between the mild surge and the deep surge cycle is that at mild surge there is no backflow, while in a deep surge cycle the pressure oscillations and the decrease of the flow rate often occur with backflow. Therefore, this examination has given almost the same conclusions as the study mentioned previously, hereafter the results of the test run have shown that the conventional view of the behaviour of the surge event is not correct exactly. Earlier studies have declared that the surge is an axisymmetric phenomenon, but the dynamic signals of this experiment have shown that the pressure oscillation period is different along the circumferential direction at the vaned diffuser inlet, and the volute induces this non-axisymmetric behaviour. Thus, if a compressor is used in a well predictable environment, an adaptive design method is applicable for the volute to solve the problem, but it is not specific in aerospace applications.

Based on the change of static pressure and the change of the characteristic of pressure oscillations and frequency, the authors have divided a deep surge cycle into three periods. It is almost the same as the aforementioned. At the start of a deep surge event, static pressure starts to increase with high frequency and low amplitude oscillations at the diffuser outlet. The authors named it as the *recovery period.* When static pressure no longer increases and starts to fluctuate with noticeable amplitude, the system is in the *oscillation period.* After that, pressure suddenly falls to a low level at the diffuser outlet, while pressure remains at a relatively constant level at the diffuser inlet and the impeller inlet, but after a sudden spike-like pressure shock, it drops to a low level too. This is the *breakdown period.* While pressure signals have shown large alterations in frequencies and altitudes, temperature signals have changed gently during a surge cycle except when the breakdown period began. At this point, a quick increase of the temperature signal was monitored, so maybe it could be used to predict or indicate the beginning of a surge event.

## 2. Currently used surge control systems

Because of the aforementioned disadvantages of surge, several different solutions [8], [9], [10] have emerged in the past decades to prevent the undesirable consequences. There are two main groups of these methods. If the system does not contain active element to detect and handle the phenomenon, we are talking about a *passive method* and consequently an *active system* has sensors and actuating devices for the purpose of detecting and controlling a surge event [11].

### *2.1. Passive surge control methods*

One of the most widespread methods to avoid the onset of surge in an operational compressor is to maintain it far from its unstable operational range. This conventional method is used especially in the aerospace industry, because this does not require additional equipment, which means in general additional weight to the whole system, and a compressor working in a jet turbine engine faces very wide range of unfavourable operational conditions, especially when the flight profile and altitude changes very quickly. The disadvantage of this safety margin is that the compressor cannot work in its whole available performance.

Other passive surge control methods are the inducer wall treatment [19] and the inducer shroud bleed. As we mentioned above, it was shown that bleeding of a small amount of the main flow has some advantages at instable operating conditions. The bleed slots attached with an annular chamber or cavity in the compressor casing can dampen pressure oscillations close to the state of the onset of surge, and they can prevent or reduce the reversing flow, which is induced by the increased static pressure in the diffuser. This backpressure can rise immediately when the incoming working medium hasn't got enough energy to overcome this resistance, for example at reduced flow rate conditions caused by unforeseeable circumferential reasons, e.g. turbulences induced by high angle-of-attack in the intake duct, which are very frequent in aerospace applications. One of the disadvantages of this method is that it decreases the efficiency of the system [20].

In the experimental study, three different bleeding slot positions were examined, and the reinjection slot position was unchanged. The results of this numerical investigation have shown that the most effective bleeding slot position is at the main impeller blade leading edge. With the setting of this slot position, the surge limit of the compressor could be increased by 8%, while the usage of other slot positions away from the main blade leading edge shows lower efficiency increment on the compressor performance map.

## *2.2. Active surge control methods*

One of the most widely used active surge control equipment is the Variable Inlet Guide Vanes (VIGV). It means there are adjustable blades in front of the centrifugal compressor inlet, which can optimise the flow incidence angle to the rotating impeller by changing the flow direction. In some cases, it means that the tangential component of the absolute flow velocity increases, which reduces the work input of the impeller. Furthermore, the usage of the VIGV decreases the output pressure, which results in lower pressure ratio. It means that the whole compressor performance map moves to lower deliveries. Besides, the VIGV adds additional weight to the whole system, which is not useful in aerospace applications (e.g. GEnx engine family) and it takes the system more complex and unable to handle any instabilities of the compression system. Because of these disadvantages, the VIGV systems reach their limits of capabilities and are not the appropriate option for further developments.

The Variable Geometry Diffuser (VGD) works based on the same theory as the VIGV. Depending on the actual mass flow rate, the velocity triangles always change at the diffuser inlet also. Especially at high rotating speeds, the instable behaviour starts at the diffuser inlet, and if the incidence angle is not optimal at the leading edge of the diffuser blades, blade stall occurs, which can cause low amplitude high frequency pressure disturbances. This can lead to compressor surge, so with the optimisation of the angle of attack of the inlet flow to the diffuser blades the onset of surge could be prevented. However, as the IGV, the VGD became ineffective if the backpressure at the diffuser outlet rises above a limit at which the working medium does not have enough energy to overcome on it. In this case, the induced backflow and the pressure disturbances could damage the parts of the compressor. Because of these negative features of the VGD system, this technology is used by only a few aerospace applications like in Auxiliary Power Units (APUs) today.

Further possible way to optimise the flow conditions in the compressor system is the rotating speed control. In relation with the mass flow rate needed in a specified application of the compressor, the alteration of the drive torque is the easiest method to keep the compressor in the stabile operational range, for example in natural gas industry. However, where the constant speed of the rotor is one of the criteria of the operation, for example in the aforementioned APUs, where the generator has to be driven at constant speed by the turbine, the speed control method is not applicable.

Amongst classical surge control solutions, some novel methods have emerged in this area in the past few years. Numerical and experimental investigations of the surge phenomenon have shown that the blade tip vortexes have major role in the transition process from stable operation to the onset of surge. A novel method aims to control these vortexes by using Active Magnetic Bearings (AMBs) [21], which enables the axial modulation of the impeller tip clearances. The experimental results have proved that it can increase the compressor performance, but in aeronautical and aerospace applications, it is difficult to implement this method.

## 3. Description of the test bench

The centrifugal compressor, which is investigated in this study, is the part of a Holset turbocharger, which originates from a locomotive Diesel engine. To operate it, we use another centrifugal compressor, manufactured by Ganz, which is working as a part of an air cycle machine cooler system for educational purposes. The air cycle machine cooling system contains also a heat exchanger and a turbine on which the working fluid drops its heat energy for the goal of cooling. The operation of these systems needs an oil system also, which was modified for the operation of the Holset turbocharger. The compressor is driven by an induction motor, which has a variable-frequency drive that allows changing its rotating speed from 0 to 30,000 RPM. At the maximum rotational speed, the Ganz compressor can provide enough airflow to operate the Holset turbocharger at the design rotational speed, which is about 50,000 RPM, but it is obvious, that the position of the throttle valve at the turbocharger compressor outlet will modify its rotational speed. To compensate this effect, and to synchronise the optimal operation of these two machines, the test bench is equipped with a Tee-tube with a valve between the Ganz compressor outlet and the Holset turbine inlet. We chose this drive system for the Holset turbocharger, because we want to examine the drop of the rotational speed and the effect of the surge avoidance system close to the real operational circumstances. This Tee tube is also equipped with a flowmeter to determine the amount of the bleed air. Another two flowmeters are used at the inlets of the Ganz and of the Holset compressors. Total pressure probes are used at the inlet and at the outlet of every main part (compressors, and turbine), and at these locations total temperature sensors are used to determine the whole performance characteristic of the entire system. The first step of the development process is the calibration of the data measurement system. The flowmeters have different geometry, so the contraction coefficient must be determined. We use a Prandtl-tube to measure the speed of the airstream that goes through the cross-sectional area of the inlet or outlet.

The rotating speed of the Holset turbocharger is measured by a magnetic sensor, and the rotating speed of the Ganz compressor is determined by calculations from the input drive frequency. We use a ferromagnetic hex nut placed at the end of the shaft of the Holset compressor as a signal generator, which, therefore, can provide 6 signals per revolution. This will be taken into account as a scale factor when evaluating the measurement of the rotational periodicity of the compressor. The speed sensor probe, which contains a permanent magnet and a coil around it, was fixed at a distance of approximately 1 mm from the nut. The magnetic field of the coil is periodically deformed by the alteration of the edge and flat side of the nut rotating in its immediate vicinity, and this periodically alternating magnetic field is inducing electric voltage in the coil by which electric current is generated. This current has nearly but not exactly sinusoidal periodicity in time, because of the geometry of the nut. The amplitude of the generated current ranges from a few millivolts to a few 100 mV with increasing RPM. During operation, the wire between the coil and the signal processor collects interference signals from the environment, which clearly justify the usage of some kind of signal conditioning method before the processing of the signal. The low signal level made it essential to use an operational amplifier, but this solution by itself is not yet suitable for filtering interference signals, so that to avoid false edge detection generated by random noise in the digital counter, it was necessary to install a Schmitt trigger circuit with a sufficiently large hysteresis. Due to its hysteresis, smaller fluctuations are actually cut off; thereby the transmission of the main, undisturbed signal could be realised. As a result of the amplifier and the Schmitt trigger, the signal, which is sent to the data collector, is a square signal with an amplitude range between 0 and the supply voltage and its frequency is equal to the frequency of the passing edges of the nut, and this signal is assumed to be symmetrical due to the geometry of the nut. The data collection was performed by a National Instruments USB 6218 multifunction data processing unit, which has an input port for digital pulse train signals. It has a built-in timer for creating the function, which is necessary to measure the elapsed time between two edges. In this function, a reciprocal calculation and scaling is required.

Temperature sensor was placed at the outlet section of the examined centrifugal compressor, this was called T2. Other temperature sensors were placed at the inlet and the outlet section of the turbine, these were called T3 and T4. During the measurement of the compressor characteristic, the throttle valve of the centrifugal compressor was moved from the opened to the fully closed position. In Figure 1 below, the effects of throttle valve movements are presented from open to fully closed position and back 3 times. As it can be seen on the diagram when the throttle valve is continuously approaching towards the closed position, temperature T2 exhibits a sudden rise, and this could be observed until the opening of the throttle valve begins. It could be also found that the power need of the compressor is also decreasing during the closing of the throttle valve, because it affects the mass flow rate of the compressor, which is in linear connection with its power consumption. This reduces the power output of the turbine and because it has constant airflow from the other compressor, the only variable which can adjust to the new equilibrium is the temperature drop at the turbine section. The ambient temperature remains constant during the measurement.

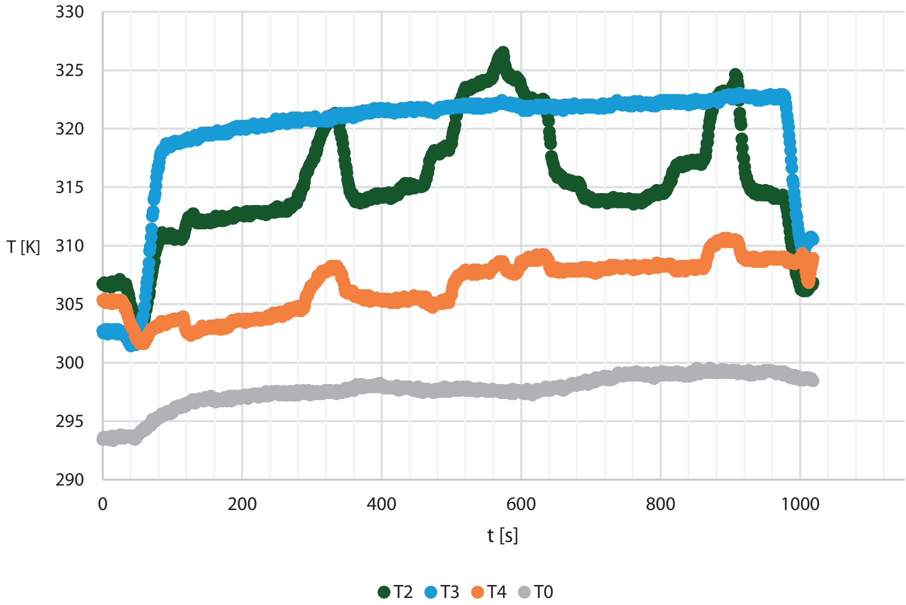


Figure 1.
*Temperature signals of the surge phenomenon* [the authors]

The Ganz compressor is the same, which is mentioned in a previous study, where the author describes a development process for the goal to enhance the stable operating envelope of the compressor. The casing was equipped with a manually controlled bleeding slot system named as the Variable Inducer Shroud Bleed (VISB) [22]. The bleed slots are positioned at the impeller region of the casing, and each bleed slot has its own cover plate attached to a central movable ring, which can move in axial direction and could be fixed with a winged nut at a desired position. This allowed the researcher to examine the effect of the bleeding slots at different rotating speeds and at different cover plate positions. The measured and processed data of the test runs verified that the usage of the bleeding slots can handle blade stall and the onset of surge close to the instable operational range of the compressor.

## 4. Investigation of possible configurations

Based on the previous studies mentioned above, it can be declared that the bleeding slots on the test bench could be used for the detection of the surge. Because of the construction features of the currently used Variable Inducer Shroud Bleed (VISB) system, it is not capable to perform fast response to the high frequency pressure oscillations. One possible way to improve this system if fast response pressure transducers combined with pressure valves are used instead of the manually adjusted cover plates. This method allows at first the determination of the exact characteristic and performance map of the examined centrifugal compressor and on the other hand, based on the measured data, the transition process of the unstable behaviour could be observed. The pressure sensors could be placed on tubes, which have the same diameter as the bleeding slots. Length of the tubes depends on the requested damping effect achieved by the inner volume of the tubes, which could be different in the circumferential direction. These pressure sensors combined with fast response micromechanical valves work independently from the others around the compressor casing. Other possible solution would be a construction of a chamber around the existing bleeding slots and the fast response pressure transducer would be placed on this chamber. But, in these cases, a significant amount of the working fluid is let out to the environment, and if we consider the formula for the calculation of the effective power of a turbomachine, it could be seen that the usage of this solution result in loss of power, which is critical at a certain application, for example in aviation.

### *4.1. Examination of recirculating bleed slots at the compressor impeller*

Based on the gained experiences of the variable inducer shroud bleed method, another surge suppression method was examined in the past few years. It uses the same principle to handle the compressor surge phenomenon, which aims to decrease the load pressure at the diffuser, but in this case, the bleed air is redirected from the compressor volute section into the impeller blade passages through holes and cavities placed in the hub of the impeller. The arrangement of these recirculating devices can be seen in a cross-sectional view in Figure 2 below.

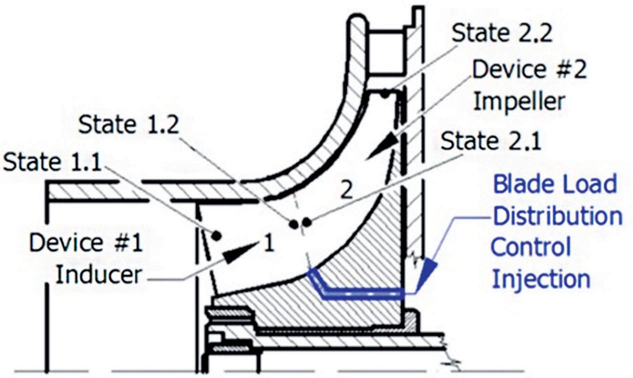


Figure 2.
*Cross-sectional view of the bleed air holes in the impeller* [23]

Figure 3.
*Front and aft views of 3D printed impeller having the labyrinth sealing* [the authors]

To control the backflow from the volute a valve is placed at the orifice of the bleed air hole in the aft body section of the volute. This „L" shaped hole ends in a flat roller shaped cavity, which has a full opening area right to the backplate of the rotating impeller. To prevent the high-pressure air from escaping this cavity towards the diffuser, on the aft face of the compressor impeller, a conical 3-stage labyrinth sealing was applied in radial direction, as indicated in Figure 3. The residual pollution particles from air in the mortises of the labyrinth sealing shows that this method could stop the leakage of the airflow from this common cavity and the main portion of this high-pressure bleed air could be forwarded right into the middle section of the impeller blade passages. The components can be seen in a partially assembled condition in Figure 4.

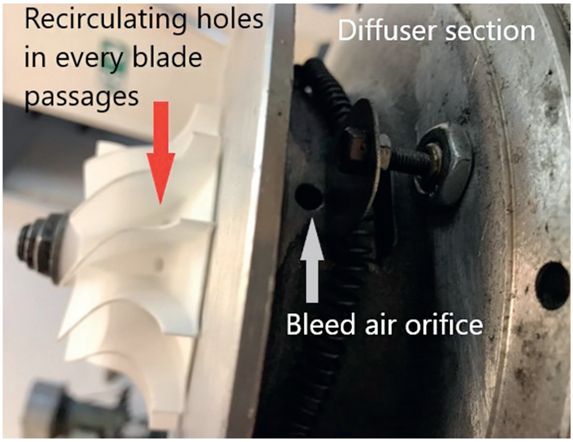


Figure 4.
*Arrangement of the recirculating system in the compressor structure* [the authors]

The choke and the variable rotating speed also allow specifying the compressor map, see Figure 5. The rotational speed of the induction motor is shown at right side of the graph in Hertz, and the gear ratio is 3.87 between the Ganz compressor and the electric motor. When 55 Hz was set on the variable frequency drive, the rotor of the turbocharger rotates 38,000 revolute per minute.

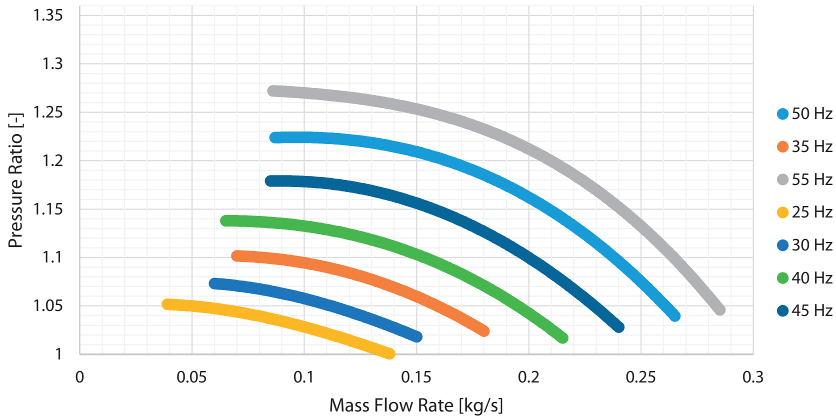


Figure 5.
*Measured compressor map* [the authors]

Our measurements have shown, that at a given rotational speed and throttle valve position the backflow from the compressor outlet could stabilise the operation of the compressor at the onset of surge condition. On the next diagram in Figure 6, pressure rise against the elapsed time is shown and the orange line shows the on or off position of the bleed air valve. As it can be seen, that by closing the throttle valve at the end section of the diffuser, the back pressure continuously rises and at a given point or at a given pressure ratio the stable operation of the centrifugal compressor suddenly turns into an unstable behaviour in which the pressure ratio falls into a lower level, and the stable mass flow rate will completely collapse and it will oscillate streamwise and in reverse direction at a dangerously high amplitude. However, if the bleed air valve was opened, which is marked by the step-up position of the orange line, it could be seen on the diagram that the operation of the compressor could be stabilised at the original pressure ratio level which was experienced at the starting point.

The bleed air valve has a simple On/Off switch and this is shown by a voltage signal in Figure 6 below, and the output voltage signal of the pressure sensor is shown in the diagram, which is proportional with the outlet pressure of the centrifugal compressor, called p2. It was measured by two total pressure probes downstream of the compressor volute section in front of the throttle valve placed in the outlet duct near the total temperature sensor. The pressure sensor has 5 V supply voltage with direct current, and the sensor sends output voltage signal in the range of 0.5 V, which is proportional to the applied pressure. This can be seen in Figure 6 below. Originally, the bleed air valve provides 5 V if it was in operation and the electrical contacts were connected, but nothing if the bleed air valve was closed. To place these lines and measurement data in one figure, the voltage signal of the bleed air valve has an offset of $U = U_{sign} \cdot 0.6 + 1.2$ [V].

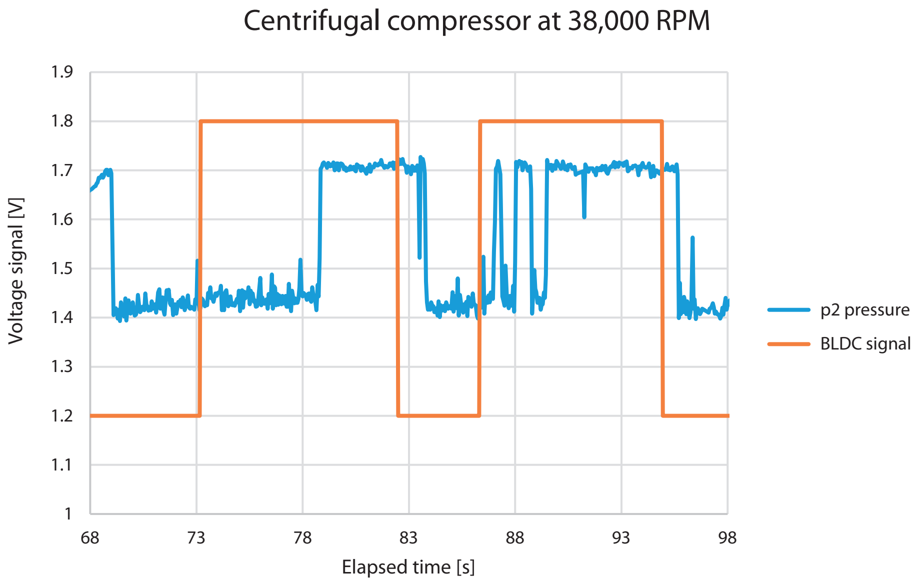


Figure 6.
*Pressure ratio of the compressor against elapsed time at different recirculating bleed air valve positions* [the authors]

## 5. Conclusion

This method was also examined by computational fluid dynamic simulations, and we have obtained the same results. Numerical calculations have also proven that this method can stabilise the operation of the centrifugal compressor at unstable working conditions, and because of the type of this recirculation method, namely the bleed air is redirected into the compression system instead of letting it out to the environment causes minimal power loss, and as it is proven by both experiments and numerical calculations, the usage of the bleed air system during normal operational circumstances yields some additional pressure rise compared to the normal operational condition at the same pressure ratio without having the bleed air system turned on.

## References

[1] S. Yan et al., 'Surge Margin Monitoring of One Turboshaft Engine with Inlet Distortion'. *Journal of Physics Conference Series,* Vol. 2472, pp. 1742–6588, 2022. Online: https://doi.org/10.1088/1742-6596/2472/1/012053

[2] B. Zhao et al., 'Experimental Investigations on Effects of the Self-Circulation Casing Treatment on Acoustic and Surge Characteristics in a Centrifugal Compressor'. *Aerospace Science and Technology,* Vol. 131, Part A. 2022. Online: https://doi.org/10.1016/j.ast.2022.108002

[3] H. Zhang et al., '*Numerical* Study *of the* Coherent Characteristics *of the* Blade Tip *of a* Micro Centrifugal Compressor *and* Its Application *in a* New Unsteady Casing-Treatment Experiment'. *Physics of Fluids,* Vol. 36, no. 1, 017139. 2024. Online: https://doi.org/10.1063/5.0190152

[4] T. Haeckel et al., 'Determination of a Numerical Surge Limit by Means of an Enhanced Greitzer Compressor Model'. *International Journal of Turbomachinery Propulsion and Power,* Vol. 8, no. 4, p. 2023. Online: https://doi.org/10.3390/ijtpp8040048

[5] Q. Peng et al., Centrifugal Compressor Performance Prediction *and* Dynamic Simulation *of* Natural Gas Hydrogen Blended'. *International Journal of Hydrogen Energy,* Vol. 52, Part B, pp. 872–893, 2024. Online: https://doi.org/10.1016/j.ijhydene.2023.10.023

[6] I. Shahin et al., 'Large Eddy Simulation of Surge Inception and Active Surge Control in a High Speed Centrifugal Compressor with a Vaned Diffuser'. *Applied Mathematical Modelling,* Vol. 40, no. 23–24, pp. 10404–10418, 2016. Online: https://doi.org/10.1016/j.apm.2016.07.030

[7] X. Zheng et al., 'Experimental Investigation of Surge and Stall in a Turbocharger Centrifugal Compressor with a Vaned Diffuser'. *Experimental Thermal and Fluid Science,* Vol. 82, pp. 493–506, 2017. Online: https://doi.org/10.1016/j.expthermflusci.2016.11.036

[8] T. Alsuwian et al., 'A Review of Anti-Surge Control Systems of Compressors and Advanced Fault-Tolerant Control Techniques for Integration Perspective'. *Heliyon,* Vol. 9, e19557, 2023. Online: https://doi.org/10.1016/j.heliyon.2023.e19557

[9] A. Renz et al., 'Improving a Centrifugal Compressor's Performance at Low Mass Flow Rates by Adding an Acoustic Resonator'. *Journal of Engineering for Gas Turbines and Power,* Vol. 145, no. 12, 2023. Online: https://doi.org/10.1115/1.4063583

[10] C. Jia et al., 'Low-Frequency Fluctuation Propagation of Rotating Stall in the Centrifugal Compressor and Pipe System'. *Physics of Fluids,* Vol. 35, 124114, 2023. Online: https://doi.org/10.1063/5.0174314

[11] C. B. Abed et al., 'Novel experimental Control Method to Suppress Instability in a Centrifugal Compressor with Two Counter- and Co-rotating Rotors'. *Proceedings of the Institution of Mechanical Engineers Part A – Journal of Power and Energy,* Vol. 237, no. 8, pp. 1715–1725, 2023. Online: https://doi.org/10.1177/09576509231181547

[12] D. Altafi et al., 'Entropy Generation Rate Analysis of Turbocharger Radial Flow Compressor in Range from Surge to Choke'. *Proceedings of the Institution of Mechanical Engineers Part A – Journal of Power and Energy,* Vol. 238, no. 3, pp. 401–426, 2023. Online: https://doi.org/10.1177/09576509231216187

[13] Y. Jeong et al., 'Supercritical CO2 Compressor Operation near Stall and Surge Conditions'. *Case Studies in Thermal Engineering,* Vol. 50, 103499, 2023. Online: https://doi.org/10.1016/j.csite.2023.103499

[14] J. Li et al., 'Surge Process of a High-Speed Axial-Centrifugal Compressor'. *Processes,* Vol. 11, no. 10, 2869, 2023. Online: https://doi.org/10.3390/pr11102869

[15] M. Zhang et al., 'Numerical Model of Predicting Surge Boundaries in High-Speed Centrifugal Compressors'. *Aerospace Science and Technology,* Vol. 141, 108518, 2023. Online: https://doi.org/10.1016/j.ast.2023.108518

[16] Y. Hayashi, T. Cao, 'An Investigation of Non-Linear Surge Characteristic in a High-Speed Centrifugal Compressor'. *Journal of Turbomachinery,* Vol. 145, no. 5, 2023. Online: https://doi.org/10.1115/1.4056089

[17] P. Silvestri et al., 'Compressor Surge Precursors for a Turbocharger Coupled to a Pressure Vessel'. *Journal of Engineering for Gas Turbines and Power,* Vol. 144, no. 11, 111014, 2022. Online: https://doi.org/10.1115/1.4055479
[18] H. Chen et al., 'Real-Time Instability Detection of Centrifugal Compressors Based on Motor Speed Measurements'. *Journal of Thermal Science,* Vol. 32, pp. 310–329, 2023. Online: https://doi.org/10.1007/s11630-022-1685-7
[19] K. Beneda, *Development of Active Surge Control Devices for Centrifugal Compressors.* PhD Thesis, 2013.
[20] H. Tamaki, 'Effect of Recirculation Device with Counter Swirl Vane on Performance of High Pressure Ratio Centrifugal Compressor'. *Journal of Turbomachinery,* Vol. 134, no. 5, 051036, 2012. Online: https://doi.org/10.1115/1.4004820
[21] S. Y. Yoon et al., 'Model Validation for an Active Magnetic Bearing Based Compressor Surge Control Test Rig'. *Journal of Vibration and Acoustics,* Vol. 132, no. 6, 061005, 2010. Online: https://doi.org/10.1115/1.4001845
[22] K. Beneda, Preliminary Results of Active Centrifugal Compressor Surge Control Using Variable Inducer Shroud Bleed'. *Periodica Polytechnica Transportation Engineering,* Vol. 39, no. 2, pp. 49–54, 2011. Online: https://doi.org/10.3311/pp.tr.2011-2.01
[23] Zs. Faltin, K. Beneda, 'Stress Assessment of Centrifugal Compressor with Surge Suppression Holes in the Impeller Hub'. in *2019 New Trends in Aviation Development (NTAD),* pp. 40–44, 2019. Online: https://doi.org/10.1109/NTAD.2019.8875526

---

## *Centrifugálkompresszoros tesztberendezés fejlesztése a változtatható, járókerék lapátközi levegőbefúvás módszerét alkalmazó aktív pompázsvédelmi rendszer vizsgálatára*

*A centrifugális kompresszorokat széles körben használják különféle ipari alkalmazásokban, amelyek magukban foglalják az üzembiztonság szempontjából kritikus berendezéseket, mint például a repülőgép-hajtóműveket. Emiatt elengedhetetlen a kompresszorok stabil működési tartományának, illetve annak kiterjesztési lehetőségeinek vizsgálata, amelyek működtetése gyakran aktív szabályozási módszereket igényel. Ez magában foglalja a korszerű digitális elektronikus mérőrendszereket, vagy akár a kompresszor esetleges túlterhelésének észlelésére alkalmas berendezéseket. Ez a jelenség általában extrém üzemi körülmények között jelentkezik, ami szerencsésebb esetben csak negatívan befolyásolhatja a kompresszor viselkedését, de akár a kompresszor mechanikai károsodásához, tönkremeneteléhez is vezethet ellenőrizetlen körülmények között. Ezért nagy hangsúlyt kell fektetni az instabilitások megfigyelésére, és lehetőség szerint olyan aktív rendszert kell alkalmazni, amely észleli és valamilyen beavatkozó szerv segítségével megakadályozza a nem kívánt üzemi állapotokat. A sok túlterhelés elleni passzív védelmi és aktív szabályozási lehetőség közül a lapátterhelés-eloszlás szabályozása változtatható levegőelvezetéssel olyan módszer, amely megfelelő mértékű hatást fejt ki az instabilitásokra, de használata közben nem jelentkezik számottevő hatásfokcsökkenés, így aktív pompázsvédelmi rendszerként is alkalmazható. Jelen cikk célja olyan könnyen megvalósítható megoldás vizsgálata egy meglévő centrifugális kompresszor-próbapadon, amely lehetővé teszi a változtatható levegőelvezetés módszerére vonatkozó elméleti megoldások gyakorlati vizsgálatát.*

**Kulcsszavak:** *centrifugálkompresszor, kompresszorok instabilitása, pompázsvédelmi módszerek, levegőelvezetés, lapátterhelés-eloszlás szabályozása*


| | |
|---|---|
| Faltin Zsolt István, MSc<br>tudományos segédmunkatárs<br>Budapest Műszaki és Gazdaságtudományi Egyetem<br>Közlekedésmérnöki és Járműmérnöki Kar<br>Repüléstudományi és Hajózási Tanszék<br>faltin.zsolt@kjk.bme.hu<br>orcid.org/0000-0002-8361-1397 | Zsolt István Faltin, MSc<br>Assistant Research Fellow<br>Budapest University of Technology and Economics<br>Faculty of Transportation Engineering and Vehicle Engineering<br>Department of Aeronautics and Naval Architecture<br>faltin.zsolt@kjk.bme.hu<br>orcid.org/0000-0002-8361-1397 |
| Dr. Beneda Károly Tamás<br>egyetemi adjunktus<br>Budapest Műszaki és Gazdaságtudományi Egyetem<br>Közlekedésmérnöki és Járműmérnöki Kar<br>Repüléstudományi és Hajózási Tanszék<br>beneda.karoly@kjk.bme.hu<br>orcid.org/0000-0003-1900-7934 | Károly Tamás Beneda, PhD<br>Assistant Professor<br>Budapest University of Technology and Economics<br>Faculty of Transportation Engineering and Vehicle Engineering<br>Department of Aeronautics and Naval Architecture<br>beneda.karoly@kjk.bme.hu<br>orcid.org/0000-0003-1900-7934 |