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DEVELOPMENT OF ACTIVE SURGE CONTROL DEVICES FOR CENTRIFUGAL COMPRESSORS

Theses of Ph.D. dissertation

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1. Motivation

The utilization of turbomachines, which can be found throughout the transportation and other important industrial applications, is constantly emerging, hence the design and operation of these units poses a persistently challenging environment. One of the possible solutions to increase the pressure of the working medium is to use dynamic compressors, which can be of axial or centrifugal design, or a compound of these two. Comparing the two extreme opportunities, the former is able to handle higher nominal mass flow rates while providing moderate pressure rise in a single stage, while the latter possesses parameters opposite to the axial machines. Based on their scope, centrifugal compressors are used in turbochargers of internal combustion engines, in small gas turbine engines ranging from auxiliary power units (APU) to high bypass ratio turbofans (e.g. Honeywell ALF502), in natural gas transportation systems [3], as well as in fuel cell applications ([2], [17]), only to emphasize the most important fields.

Compressors are not used alone; they are part of a compression system, which is shown in general arrangement on Figure 1. User devices, which form the downstream part of the system, present a very wide range of operational circumstances which often result in the instability of a dynamic compressor. Based on the system configuration, these phenomena can be rotating stall, surge or the combination of these two, as it has been investigated by several authors ([4], [7], [13], without attempting to be comprehensive). Both of them yield severe restrictions on the avoidance and, when they still occur, their consequences are serious, though, due to the involved energy of the oscillating mass flow, surge can be considered as more harmful, because

- if the drive is independent from the compressor (e.g. induction motor driven compressor in fuel cell application [2]), the operation within surge may take a prolonged time leading to mechanical failures due to the highly transient load conditions causing fatigue;

- if the compressor is installed in a gas turbine engine, the periodic mass flow fluctuations result shortly in a combustion chamber flameout and a (possibly in-flight) shutdown of the engine, that bears extremely high risk.
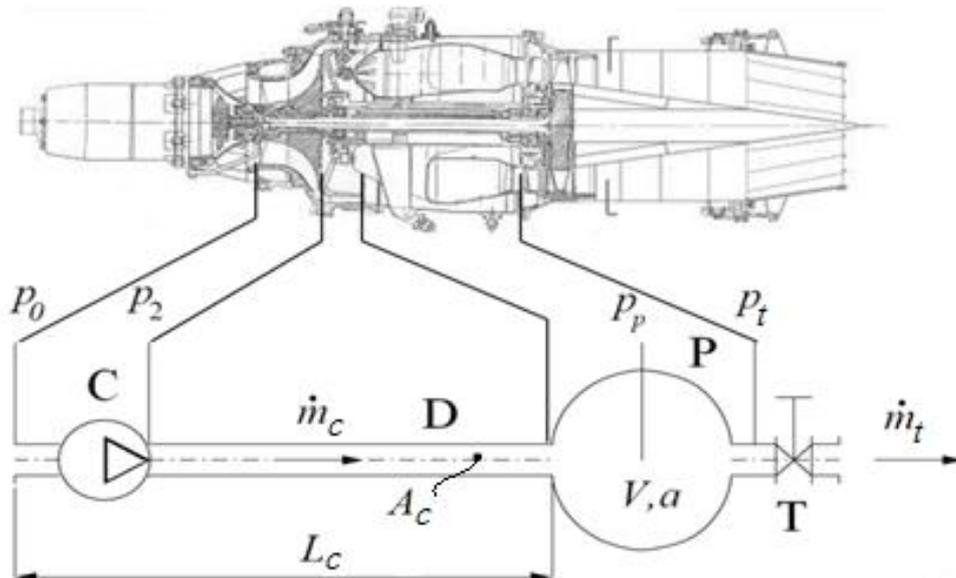

Figure 1 Schematic of compression system (based on [9])

Because of the impact on both instantaneous performance and long-term service life of the unit and receptive system detailed above, the onset, behavior and possible avoidance of the instabilities has been of emphasized importance among theoretical and experimental investigations. As the results of researches have presented an increasing detail of the phenomena, so could the evasive solutions

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offer better efficiency while providing a more robust stabilization. From the late 1980's besides the conventional passive avoidance methods [10] actively controlled suppression systems have been introduced (e.g. [6], inducer tip injection [8], close coupled valves [15], recycling valves [5], etc.), which yield a stronger support against instabilities involving their capability to dynamically adapt the system to the different load conditions in a comparably shorter time than the previous methods.

The strict regulations and other design requirements make the fast acting, low energy consumption active surge suppression inevitable. Hence the available and currently utilized methods have to be refined and also new approaches have to be developed. It is also possible that under certain circumstances conventional passive solutions can be used as the basis for new active systems.

The above mentioned requirements of the surge suppression necessitate such systems, which are able to rapidly react, in order to cope with the highly dynamic phenomenon, while consuming as little energy as possible resulting in an optimal efficacy of the system.

In the present thesis, the main goal is to find, design and evaluate alternative methods for active surge suppression, which has not been utilized before but may meet the aforementioned requisites. The author has first met these problems and possibilities in theory during the aeronautical studies at BME, than in experiments as he was involved in the development of a turbojet engine at the predecessor of Department of Aeronautics, Naval Architecture and Railway Vehicles. The steps of this particular development can be evaluated based on the list of further publications.

The aims of the thesis can be classified in details as follows:

1. Based on an extensive, literature-based comparison of the widely-spread possibilities of passive surge avoidance and active surge suppression methods, decision has to be made for the selection of the appropriate solutions. The main interest is in such passive opportunities, which have not been realized yet as an active system.

2. The selected principles have to be examined in the first step with the help of a one-dimensional mathematic model especially developed for this purpose. In order to provide the ability of comparing results to other models, the realized one must offer the potential for investigating conventional solutions also.

3. The one-dimensional approach has to be broadened and a thorough, three-dimensional numerical simulation has to be accomplished using commercial CFD software.

4. The results of mathematical model and CFD simulation both are to be validated with the help of a compressor test rig, consequently the design and development of such a system with up-to-date data acquisition is an emphasized goal of the present work.

5. After the validation of the mathematical models, the final investigation covers the establishment of a control system.

The main hypothesis of the present work is that new active surge suppression solutions can be derived from conventional passive methods, which have not been utilized before as controllable systems. Also important assumptions are that a possibility can be found to convert passive devices into active ones and the control system may be based on an LQR approach, regarding that the compressor model can be linearized in the vicinity of a selected stable operating point.

The expected results are that the selected passive methods can be realized with up-to-date methods including devices based on MEMS technology resulting in a fast response, low power requirement, highly efficient surge suppression system, which can be controlled optimally in a linear quadratic sense. Additional outcome of the work should be the characterization of the investigated methods, applicability, potential limits, feasibility, etc.

2. Utilized methods

In order to determine the applicability or limits of possible utilization of a potential surge suppression device, an intensive investigation involving several aspects of survey has to be carried out. The research shall exhibit the necessary steps of detail deepness, i.e. the examination should first be focus on a simplified approach of the problem ascertaining general features of the system. This can be accomplished with a special mathematical model derived from conventional compressor calculations, focusing on the effect of the integrated surge suppression devices. This one-dimensional model is realized in MATLAB environment, which offers powerful mathematical background to the computation software. As both investigated methods (Variable Inducer Shroud Bleed and Blade Load Distribution Control) are to be realized in the interface between inducer and impeller of the centrifugal compressor, a split compression model approach is reasonable, as shown on Figure 2.
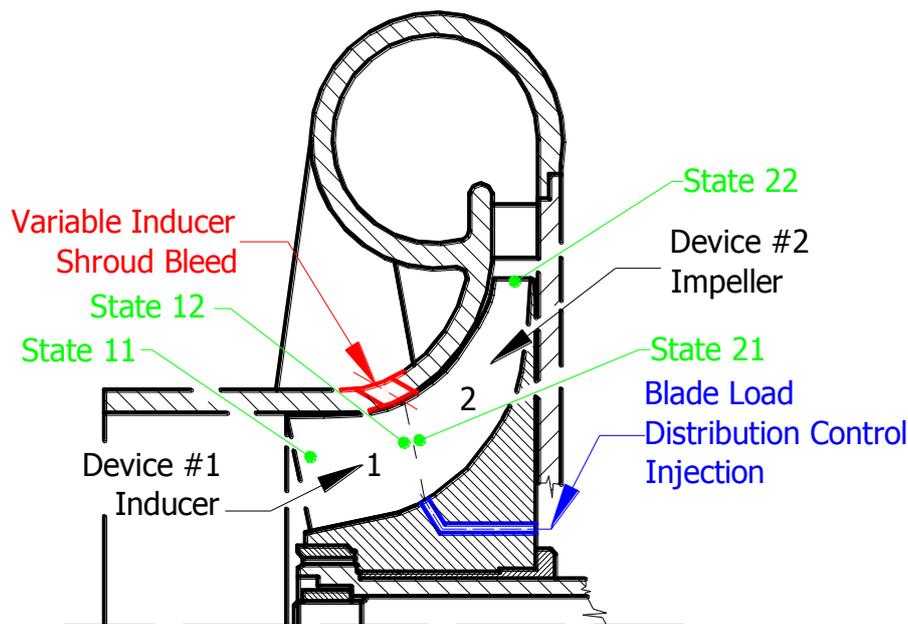

Figure 2 Split Compression Model used for simplified one-dimensional approach of surge suppression devices

Following the simplified model, a detailed investigation on the fluid dynamic problem based on CFD simulations has to be accomplished focusing on the static and dynamic behavior of the studied surge suppression devices. In the preliminary part of the research the effect of the given method on the compressor's steady state characteristic should be focused, succeeded by the detailed exploration of the transient operational modes including up- and downstream system components from the environment of the compressor. The Department possesses research license for ANSYS CFX commercial software, which was the basis for the simulations.

In order to ascertain matching results with reality, the output of the CFD simulation has to be validated with data acquired in measurements. The development of the validation hardware, which incorporates a compressor test bench including the necessary data acquisition and control system also, has an emphasized importance. In order to accelerate hardware and software development for the measurement system, flexible USB-based data acquisition tools for personal computers can be applied with the operating software realized in LabVIEW for user-friendly and seamless integration of the system.

As the previous researches have been concluded, the results can be used for the design of a possible control system that will provide the expected stability, robustness and effectiveness of the surge suppression. The dynamic model of the system and the development of the controller can be

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[B12e] BENEDA, Károly: Control of Centrifugal Compressor Surge Using MEMS Devices. Proceedings of the 13th Mini Conference on Vehicle System Dynamics, Identification and Anomalies (VSDIA), Budapest, 2012, *under issue*

[B12f] BENEDA, Károly: Centrifugálkompresszor fali megcsapolás vizsgálata numerikus áramlástani módszerekkel. Repüléstudományi Konferencia, Szolnok, 2012. HU ISSN 1789-770X, pp. 824-843.

4. Future developments

As all investigations, the present work also could not answer all possible questions of the selected topic, hence a broad range of future developments can be found. When one examines the neglected features also can find the answers of the ways of further improvement. Related to the above detailed theses, one can consider the following.

The VISB system has been implied as a set of relatively small number orifices having considerable measures. It could be more practical if a large number of small outlets could be realized based on MEMS actuation resulting in smoother and more accurate control consuming less power during operation.

As the field of control has been considered only superficially, a large improvement could be achieved in this subject. Because in the present work only a single linear approach has been evaluated, expanding the scope with other solutions, e.g. linear parameter varying (LPV) control, which is experiencing emerging utilization throughout the aerospace industry [1], would be beneficial, and, regarding the nonlinear nature of compressor instabilities, development of a nonlinear control could be also feasible.

The alternative surge suppression method, Blade Load Distribution Control has also open questions, mostly in the implementation of the system. It can be an emphasized way of further development to realize the designed BLDC system on a compressor in order to be able to gain experimental results on the operation of such devices. Another improvement of the current design concerning different setup of injection could be investigated.

Both MATLAB computation and LabVIEW data acquisition software have been written to meet the requirements of the present study, therefore the adaptation to newly defined needs can be a basis for further development of them. Both can be used also in other applications, i.e. complete mathematical model or measurement system of a gas turbine engine, respectively.

The compressor test rig is also able to involve important improvements. Besides the above mentioned possibility of implementation of BLDC, probably the most substantial development would be the realization of such equipment for the VISB, which is able to react rapidly on the requirements having put up by the surge suppression control.

5. Publications related directly to the thesis

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[B08a]   BENEDA, Károly: Dynamic Nonlinear Mathematical Model of Active Compressor Surge Control Devices. Proceedings of the 11th Mini Conference on Vehicle System Dynamics, Identification and Anomalies (VSDIA), Budapest, 2008, pp. 583-591. ISBN 978-963-313-011-7.

[B08b]   BENEDA, Károly: Dinamikus matematikai modell centrifugálkompresszorok aktív pompázs-szabályzó rendszereinek vizsgálatára. XV. Repüléstudományi Napok, Budapest, 2008. ISBN 978-963-420-857-0

realized in a MATLAB Simulink environment, which offers powerful tools in the related field of engineering. Although the nature of surge exhibits severe nonlinearities, when suppressing the instabilities one can assume the operation can be approximated with a linear model. Based on this assumption, an optimal control in linear quadratic (LQ) sense can be developed for the investigated surge suppression devices.

3. New Scientific Theses

The development of Variable Inducer Shroud Bleed active surge suppression method

Inducer shroud bleed is a widely spread passive surge avoidance solution used on turbochargers of internal combustion engines [11] and also on starter gas turbines [B10d]. It can be realized as either an opening to the atmosphere or as a closed chamber. The former provides stabilization over higher range but leads to considerable efficiency drop at high delivery rates. The latter is effective only during transient processes; it is not usable for prolonged operation below the surge point, therefore it is intended mostly for avoiding instabilities during engine startup only. Consequently, an actively controlled variable implementation could result in flexible operation; i.e. with opening the variable inducer shroud bleed orifices at low mass flow rate can stabilize the flow, while at high deliveries the closure enables high efficiency.

Thesis 1. *I have developed a method of Variable Inducer Shroud Bleed (VISB) for active suppression of centrifugal compressor surge, based on the widely spread fixed (passive) inducer shroud bleed surge avoidance solution.*

  a. I have implemented the originally fixed orifices in the method of VISB as controllable bleed valves in order to achieve active surge suppression capability that is controllable throughout the whole operational range of the compressor.

  b. The VISB allows the extension of the range of stable operation by approximately 10 percent of the uncontrolled surge mass flow rate, which has been predicted by the simulations and has been validated through extensive experimental research with a compressor test bench.

  c. The most important advantage of the VISB over its constant geometry predecessor is that it allows an efficiency increase at high delivery rates when the orifices are controlled closed. When compared to realized, active surge suppression systems, it shows (by use of ANSYS CFX commercial code) a favorable effect on the efficiency due to the less work done on the part of the medium to be released through the VISB in order to suppress instabilities.

Publications related to Thesis 1: [BN08], [B08a], [B10b], [B11a], [B12f]

The foundation of LQ optimal control of VISB surge suppression

During the design of a surge suppression system it is inevitable to investigate the possibilities of controls. Although the phenomenon of surge exhibits intensive nonlinearities [14], the operational regime preceding the instabilities can be studied using linear approaches, which is often utilized [12]. In the present work a regulator optimal in linear quadratic sense has been investigated in order to provide control for the VISB surge suppression method.

Thesis 2. *I have designed a linear quadratic regulator (LQR) for the optimal control of the VISB method, based on the modification of the Greitzer model for centrifugal compressor surge, including rotor dynamics.*

a. For control input I have introduced the dimensionless VISB opening, γ_{VISB}, instead of conventionally applied mass flow rate or compressor discharge pressure. The linearized state space representation of the compressor model has been derived for this single input in MATLAB Simulink environment. As changes in rotor speed have been negligible proven by measurements, finally the model has employed a constant speed approach.

b. I designed the present control to be able to operate based on the conventional measurement of rotor speed, mass flow and compressor discharge pressure, which is common to realized systems, as well as it can rely on the data yielded by micro electro-mechanical (MEMS) sensors in the inducer-impeller interface installed on the shroud of the compressor, where the VISB orifices are located.

c. The designed control, in spite of current surge suppression systems, achieves lower power consumption for stabilizing the flow which decreases power requirement by 7.5% leading to an overall efficiency increase under transient operational conditions. This fact has been validated using measurements carried out on Boeing 737NG aircraft APU's.

Publications related to Thesis 2: [BN08], [B11b], [B12c], [B12e], [B13b], [B13c], [B13d]

Development of active Blade Load Distribution Control surge suppression method

Surge suppression using injection at the compressor eye is extensively investigated [16] but the injection realized in the inducer-impeller interface could result also in the stabilization of the compressor flow at deliveries below the surge point. This solution originally has been developed as a special geometry impeller introducing a short convergent section within the blade passage. Although it showed significant enhancement on the compressor map it could not spread widely due to the high inertia. Substituting a variable injection in the blade channel involves flexibility and controllability leading to better stability and efficiency of the compressor.

Thesis 3. *In addition to the VISB, I have developed an active method for Blade Load Distribution Control (BLDC) and investigated extensively with CFD, which is based on the research of Flynn and Weber [11], where a passive solution has been realized in order to separate the stall regions of the inducer and impeller.*

a. I assumed in the BLDC method the utilization of perpendicular flow injected from the hub of the compressor at the inducer-impeller interface within all blade channels to create a deflection of the base flow resulting in dynamically adjustable geometry of the passage. This effect results in the division of stall regions leading to stabilization of the compressor.

b. I have performed thorough CFD simulations in ANSYS CFX commercial code and I have realized the simplified one-dimensional mathematical model of the BLDC. As the operation of the BLDC is similar to several jet-in-a-crossflow problem, they provided a basis for validation of the numerical investigation, due to the lack of own hardware.

c. As the method of BLDC implies a dynamic internal flow path modification that can be mathematically described in a similar manner to the effect of the VISB (i.e. it results in a movement of the compressor characteristics towards lower deliveries), it is also optimally controllable thus the method described in Thesis 2 is assured.

Publications related to Thesis 3: [BN08], [B11c], [B12a], [B13a]

Software support for mathematical model and data acquisition

Current engineering practice is impossible without the help of computer systems. Considering either design of a new product or investigating an existing one, the possibilities are intensely expanding using the appropriate software. Therefore during both the theoretical research and experimental work the available up-to-date solutions have been utilized thoroughly.

Thesis 4.   *I have developed a small software bundle called Split Compression Model for data acquisition and control, in order to supply theoretical computation and provide data acquisition for experimental purposes.*

    a. I have written the module for theoretical computation in MATLAB that contains a one-dimensional approach of the methods VISB and BLDC, which treats the centrifugal compressor as a pair of two coupled compression units, split to the inducer and the impeller, respectively.

    b. The developed simplified one-dimensional computation also constitutes the basis for the designed control system.

    c. I have realized the data acquisition module in LabVIEW that includes the necessary components to conduct detailed measurement of the investigated method and provides automatic data storage during the measurement for subsequent off-line evaluation.

Publications related to Thesis 4: [B08a], [B08b], [B10b], [B10d], [B12b]

Development of validation hardware

In order to ensure the reliability of the results supplied by various mathematical approaches of the investigated active surge suppression methods, it is important to conduct measurements on a system implementing similar conditions to the theoretical setup of the systems. As the realization of BLDC raised difficulties only the VISB system has been implemented.

Thesis 5.   *I have elaborated a measurement principle and I have implemented it on a compressor test bench in order to provide experimental research capability of the VISB system. I have used the measurements conducted on the test bench for validation of the numerical simulations.*

    a. I have realized the VISB system on the compressor test bench; and I have developed a coupled data acquisition system. The measurements provided a basis for validation of the theoretical results.

    b. With the help of the VISB system, the compressor test bench can be utilized for the investigation of generation and suppression of various instabilities including rotating stall and surge due to the throttle valves located in different installations.

    c. The test bench is also capable of the survey of various aero-meteorological phenomena (icing, high humidity environment, etc.) that can lead to instabilities of aircraft engines and their components.

Publications related to Thesis 5: [B10a], [B10c], [B11b], [B12b], [B12d]