Proceedings of Global Power and Propulsion Society
ISSN-Nr: 2504-4400
GPPS Xi'an21
18th – 20th October, 2021
www.gpps.global

GPPS-TC-2021-296

A REVIEW OF THE ANALYTICAL AND NUMERICAL METHODS FOR AXIAL COMPRESSOR SURGE

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ABSTRACT

Surge is an unstable phenomenon which is catastrophic to the aero-engines and gas turbines. It can lead to deterioration in performance and engine life as well as mechanical failure, which has long been the research focus of the industrial and academia. One of the most crucial objectives is to figure out the mechanism of the surge and predict its occurrence. Based on the observations in rig tests and engine operation, different theories were proposed to investigate the mechanism and a few classical analytical models were created for modeling and prediction; With the fast development of the numerical methodologies and the boost of the computational resource, Computational Fluid Dynamics (CFD) has been employed to simulate the surge process of the axial fans and compressors.

In this review, the principles of the surge phenomenon and general observations are firstly introduced. Thereafter various analytical and CFD methods are presented. The advantages and shortcomings of these methods are listed and discussed. In the conclusions, we proposed potential improvements and technical routes for further study. This paper aims to provides a useful reference for future work on axial flow compressor surges.

Keywords: surge; axial flow compressor; analytical; CFD

INTRODUCTION

The unstable phenomenon of the compression system in the aero engine and gas turbine is mainly classified into rotational stall and surge. Surge phenomenon is characterized by one-dimensional axial direction, high amplitude and low frequency (Sanmai, et al. 2014). Surge can lead to rapid heating of the blade, increasing compressor outlet temperatures, causing blade vibration and fatigue, and ultimately causing serious damage to the compressor and the engine (Kirn and Fleeter, 1994). A description of the occurrence of surge on a flight is as follows :"It felt just like we had hit a telephone pole with the right wing, ... it was short and abrupt, but scary as hell" (Langston, 2017).

The causes of surge can be attributed to many different factors, such as acceleration-deceleration, fuel pulsation, intake distortion, inflow bleed, and so on. Once the surge occurs, it will seriously damage the engine performance and shorten the service life, so it is required to ensure a safe surge margin (Huang and Huang, 2013). For modern aviation multi-stage axial flow compressors, the surge margin is typically up to 25%, as shown in Figure 1 (Ucer, et al.1985).

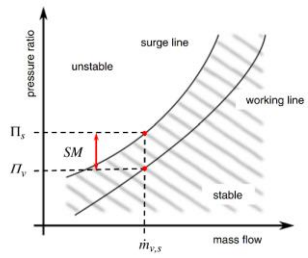

Figure 1 Characteristic operating range of a compressor

$$SM = \frac{\Pi_S - \Pi_V}{\Pi_V} \cdot 100[\%] \qquad (1)$$

Where Π_s and Π_v indicate the pressure ratios on the surge line and the working line, respectively.

According to the fluctuation of mass flow rate and pressure ratio, surge can be classified into four different types (Tavakoli et al., 2004) as follows:

1. Mild surge: there is no backflow of mass flow, and the pressure ratio fluctuation presents a small amplitude and periodicity.
2. Classic surge: there is no backflow of mass flow, the oscillations at a larger amplitude and a lower frequency than that in the mild surge.
3. Modified surge: a combination of rotating stall and classic surge, the whole annular flow fluctuates in the axial direction, and the flow is characterized by unstable and non-axisymmetric.
4. Deep surge: there is backflow of mass flow, unsteady but axisymmetric limit cycle flow.

Researchers have generally studied classical surge and deep surge, and their differences are displayed in Figure 2.

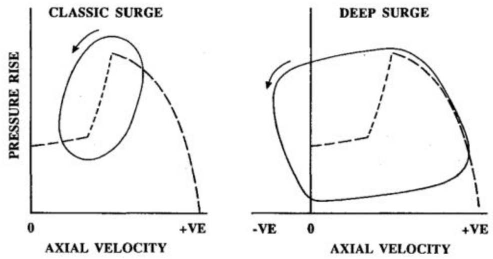

Figure 2 Difference between classic surge and deep surge

To reveal the physical mechanism of the surge phenomenon, researchers have conducted numerous studies by different methods such as experimental, theoretical, and numerical simulations. There are issues such as danger, the complexity of the operation, and high cost of experiments. Comparatively, analytical and numerical simulations have the advantages of safety, simplicity, low cost, and provide a more detailed flow field. The rapid prediction of surge through analysis and numerical simulation can provide valuable guidance in the design phase of the compressor. By now, the analysis and numerical simulation can not accurately reflect the surge process, this paper aims to provide some inspiration for relevant researchers by organizing and summarizing previous research.

Analytical model

Based on an empirical correlation of inlet surge overpressure and operating conditions, Mazzawy proposed an analytical model to analyze the surge mechanisms (Mazzawy, 1980). He pointed out that the shock propagation velocity regarding a fixed reference frame at any axial position of the compressor can be calculated by equation 2. After that, the total impulsive load application time can be calculated by equation 3.

$$V_{\mathrm{SHOCK}} = \left(\mathrm{M}_{\mathrm{SHOCK}_{\mathrm{REL}}} - \mathrm{M}_{\mathrm{FLOW}}\right) \cdot C_{\mathrm{LOCAL}} \qquad (2)$$

$$\Delta T_{\mathrm{load}} = \frac{\text{Axial Length of Compressor}}{V_{\mathrm{shock\ inlet}}} \qquad (3)$$

Greitzer developed an analytical model in which he proposed a dimensionless parameter, the B parameter, to judge whether a rotational stall or a surge occurs in an axial compressor(Greitzer, 1976). The explanation of this parameter is the ratio of pressure to inertial force, and the specific expression is given in equation 4. The compression system he used to analyze is shown in Figure 3. The compressor is attached to the plenum through a duct, and the volume of the plenum is much larger than that of the compressor and duct. The pressure in the plenum is considered spatially uniform and changes with time. The flow is controlled by a throttle downstream of the plenum. He used a component approach to describe the flow disturbances and eventually combined them to obtain the three main equations used to analyze the system state. The physical meanings of the three main equations are the local momentum balance of the system; the annulus-averaged momentum balance; the mass balance of the plenum.

$$B=\frac{U}{2a}\sqrt{\frac{V}{AL}} \qquad (4)$$

Where U is the wheel speed at mean diameter, a is the local sound speed, V is the volume of plenum, A is the area of compressor duct, L is the length of compressor duct. Based on this, Moore and Greitzer collaborated to establish a 2D nonconstant incompressible nonlinear model, the well-known M-G model, which provides a robust theoretical support for the subsequent study(Greitzer and Moore, 1986). The shortcoming of their work is that only pure modes exist, either surge or rotational stall, but the actual situation is not so simple.

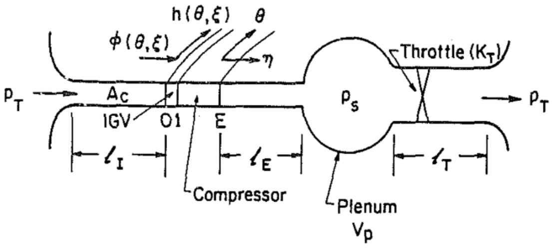

Figure 3 schematic of compression system from

A one-dimensional, stage-by-stage axial compression system analytical model has been proposed by Davis and O'Brien to characterize the poststall events, including surge and rotating stall (Davis and O'Brien, 1991). The governing equations are generated by applying the principles of conservation of mass, momentum, and energy to the elemental control volume. Classical(Figure 4) and deep(Figure 5) surge model cases have been compared to experimental results from the work of Greitzer and Moore, respectively.

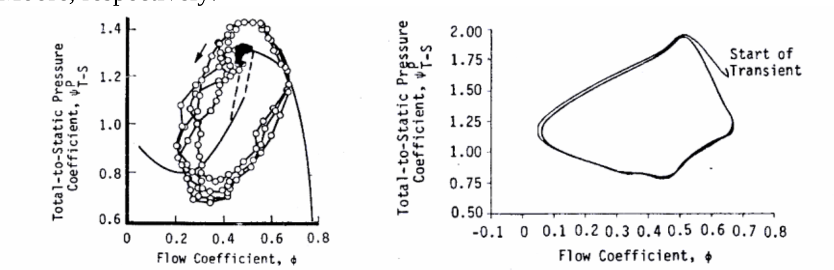

Figure 4 experimental and model results (classic surge, B = 1.0)

In the experiments, the authors induced a deep surge (B=1.58) by decreasing the throttle to 60% of the minimum system instability. As you can see in the figures, the modeling technique has been validated in operation by comparing it with existing experimental results. To further explore the potential of the model, the authors conducted a parametric study to evaluate the effect of heat transfer due to rapid power lever transients and tip casing treatment on the system behavior. The author admits that the model has two shortcomings: the surge frequency is hard to model accurately; the reverse flow part is not as accurate as the normal flow part.

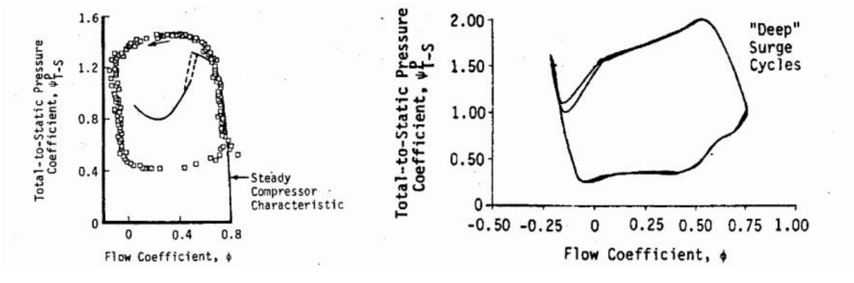

Figure 5 experimental and model results (deep surge, B = 1.58)

Sugiyama simulated surge disturbance propagations throughout an entire turbojet engine (Sugiyama et al., 1989). In the one-dimensional model, the lumped-volume approach is adopted. Compressor stage characteristics are used to provide force and work for the engine components actuator disks. The inlet and exit conditions are switched in the case of reversed mass flows during surge transients. Different stall methods were also investigated and they were found to result in different compressor operating-point excursions. Dundas designed a mathematical model of a single shaft gas turbine and evaluated eight deterioration types through the compressor operating line. It was found that reducing the flow capacity of the compressor through fouling or by eroding and closing the turbine nozzle diaphragm moved the operating line to surge(Dundas, 1986).

Body force method

The body force method (BFM) is a method based on the principle of superposition, and the framework and basic methods of BFM are introduced in the article by Nisitani (Nisitani and Chen, 1997). And a general description of the concept of body force representation of blade row is written in the article of Marble (Marble and Hawthorne, 1964). Gong developed a body force formulation to simulate unsteady disturbances in stage 35 compressor(Gong, 1999).

Longley proposed a blockage-mixing model to figure out the entropy increase in "steady" reverse flow(Longley, 2007). In reverse flow, the authors assume that the flow separates at the trailing edge, thereby creating a free shear layer in the cascade, forming an ideal "square wave" profile when leaving, as shown in Figure 6. The blockage associated with the jet wave structure can be described by the parameter b, in which the jet occupies a portion of 1/b of the channel width. The specific expression of the parameter b is given in equation (5).

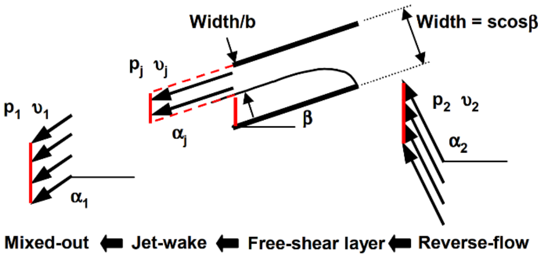

Figure 6 blockage-mixing model for reverse flow through a cascade of flat plates

$$b = 1 + \left| \frac{\sin\left(\alpha_2 - \beta\right)}{\cos\alpha_2} \right| \qquad (5)$$

The physical meaning of the blockage parameter, b, is the ratio of the actual momentum of the flow to the momentum of the local uniform flow. The influence of the short length flow is integrated into the medium-long length scale motion equation through the blockage parameter. Although the surge phenomenon is a larger scale disturbance, the short scale length-scale increases the momentum and kinetic energy of the flow. It is the mixing of these short length-scale non-uniformities that is the important mechanism for entropy generation in the reverse flow process. The authors averaged the equations of motion over a nominal volume that included one or more blade pitches, as shown in Figure 7. Finally, the novel expression of the blockage-transport equation is given in equation 6.

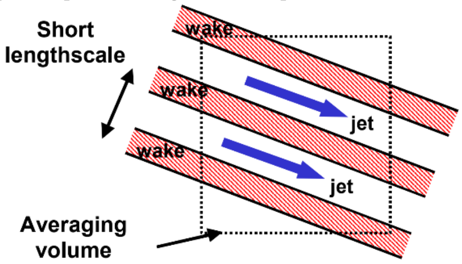

Figure 7 Volume over which the short lengthscale flow non-uniformity (large separations) are averaged

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho(b-1)\bar{\mathbf{u}}^2\right) + \frac{1}{2}(b-1)^2\bar{\mathbf{u}}^2\nabla\cdot(\rho\bar{\mathbf{u}}) + \left(\frac{b-1}{b}\right)(\rho\bar{\mathbf{u}}.\nabla)\left(\frac{1}{2}b^2\bar{\mathbf{u}}^2\right) = -\bar{\mathbf{u}}.\mathbf{F} - \rho T\frac{Ds}{Dt} \qquad (6)$$

Righi established a 3D through-flow code called ACRoSS to model the surge in axial compressors by using the body force method to simulate the effects of blade rows (Righi et al., 2018, Righi et al., 2020). In the actual operation of the compressor, the circumferential flow is non-uniform. To reflect this, a random algorithm is triggered at regular intervals in ACRoSS, which introduces a distortion in velocity and pressure with a sinusoidal distribution in the circumferential direction in each blade row. The authors simulated deep surges of different volumes, as shown in Figure 8. It can be seen that as the volume decreases, the behavior becomes more pronounced. In more detail, a higher overshoot in the blowdown phase and a more declined surge cycle, and this phenomenon is consistent with what Day(Day, 1994) has discovered in their experiments. But when the volume is too small, 1 m^3 in their cases, the flow is not fully reversed and a steady rotational stall is formed during the recovery phase. Their results are compared with URANS simulations conducted at Imperial College, and the through-flow codes have significant advantages in terms of computational cost and time for the same results.

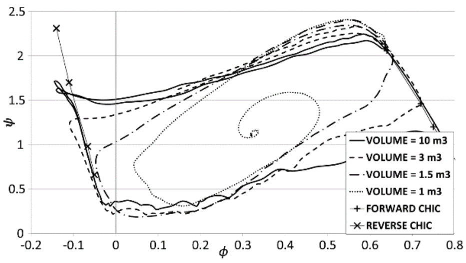

Figure 8 surge cycle simulations with different plenum volumes

Wang used a hybrid BDF/harmonic balance method to simulate the characteristics of an axial flow compressor(stage 35) that operated under surge conditions(Wang et al., 2020). The author performed studies on the effect of plenum volume and average mass flow rate on the compressor, respectively. The simulation results show that as the average mass flow rate decreases, the surge period increases, and the surge frequency decreases. Once the average mass flow rate decreases to a certain value, the surge period will no longer change; as the plenum volume increases, the surge period gradually increases. However, the outlet static pressure has significantly decreased in oscillation amplitude; accordingly, the surge frequency goes down. These are consistent with the results of previous work by researchers (Greitzer, 2009).

RANS/URANS

Niazi simulated the compressor surge using Reynolds averaged Naiver-Stokes (RANS) code(Niazi, 2000). His method captures the large surge flow oscillations in the reverse flow in the compressor, however, the results are not validated by experimental data. Vahdati performed instability simulations of an eight-stage high-speed axial compressor using a 3D viscous time-accurate RANS CFD code(Vahdati et al., 2008). In the simulation, a surge point at each operating point in the velocity line requires the nozzle exit to change the diameter and repair the nozzle, but this is somewhat impractical. Dumas used a commercial CFD code (ANSYS CFX) to predict the surge load in a low-speed, three-stage axial compressor(Dumas et al., 2015). The simulation results show a good correspondence with the experimental data in both the shape and magnitude regarding the total static pressure rise and the flow coefficient. However, the oscillation frequency prediction is not accurate, the simulated result is 3.88 Hz, while the experimental measurement with a hot wire is 1.17 Hz. The author states that this difference means that the B parameter cannot be used as a simulation factor when it comes to surge cycle frequency.

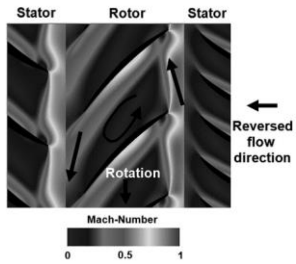

Figure 9 Flow field at backflow conditions of the rotor

Schoenenborn and Breuer investigated the blade loading during surge process by using the 3D RANS method (Schoenenborn and Breuer, 2012). Figure 9 shows the flow field of a rotor blade and two adjacent stator blades. It can be seen that in the rotor blade, the airflow enters the trailing edge area of the blade with a higher Mach number, which causes a large recirculation area on the suction side of the blade with a lower Mach number, while a small area of higher Mach number can be seen along the pressure side of the rotor. Later, Schoenenborn and de Vries used CFD to calculate the aerodynamic damping of the flow in each phase of the surge, and both experimental and simulation analyses have shown that the surge stress in the blade can be greatly reduced by using intentional mistuning(Schoenenborn and de Vries, 2013).

Crevel studied the surge cycle in a high-speed, high-pressure, multistage compressor by the time-accurate 3D compressible unsteady Reynolds averaged Naiver-Stokes (URANS) method, and most of the simulated phenomena agreed with those observed in the experiments, thus confirming the quality of the numerical method(Crevel et al., 2014). Zhao used 3D URANS to investigate rotating stall and surge events of an 8-stage high-speed axial compressor at off-design operating points, including blade force and response changes(Zhao et al., 2018). Figure 10 shows the computational domain of the compressor, the one-channel computational domain contains about 5 million nodes, so the entire compressor has about 300 million nodes for the full annulus model of the entire compressor model.

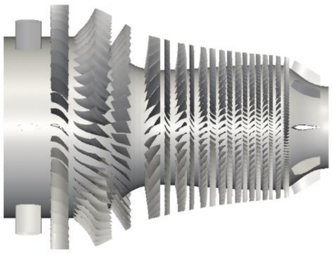

Figure 10 The computational domain of compressor

Moreno investigated the aerodynamics of a three-spool modern engine compression system using 3D URANS solver during high power surge (Moreno et al., 2020). He investigated the effect of two different forms of surge triggers, abrupt throttling in a high pressure compressor (HPC) and the angle of adjustment of the variable stator vanes (VSV) in a medium pressure compressor (IPC), on the surge load on the core compressor. He found that the maximum aerodynamic load (maximum overpressure) on the compressor during the surge cycle is caused by the combined effect of the surge shock wave and the high-pressure gas blowing forward, seen in Figure 11. This differs from the view accepted in previous papers(Huang and Mazzawy, 2018) that the surge shock wave is the root cause of the maximum aerodynamic load.

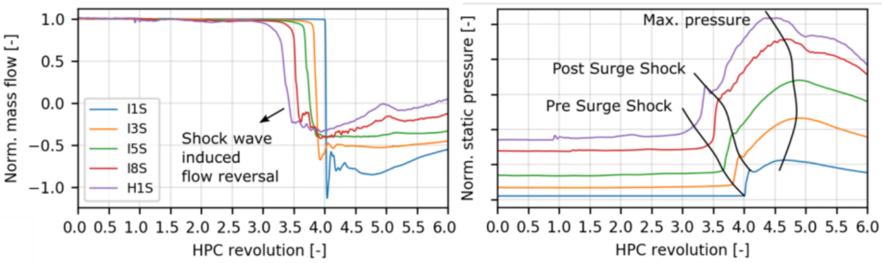

Figure 11 Transient area average quantities at the inlet of several IPC stations and H1S

In addition, due to the higher pressure in the compression system during high-power operation, the surge shock wave in the HPC is generated almost instantaneously and propagates in an approximately axisymmetric form, increasing in intensity the further it travels toward the front of the engine.

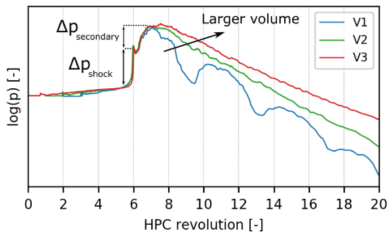

Figure 12 Transient area averaged static pressure (log-scale) at H1S inlet

In the end, the authors investigated the effect of plenum volume on the overpressure caused by surge. Figure 12 shows transient area averaged static pressure at the H1S inlet. It can be seen that the change in the degree of surge shock induced spike and secondary pressure rise is very small in the three cases, and the authors concluded that the plenum volume has very little effect on the overpressure amplitude.

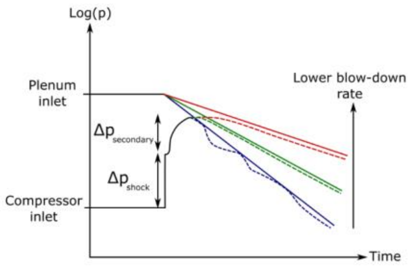

Figure 13 blow-down effect on surge overpressure

However, the authors observed that the plenum volume has a great impact on the performance of the compression system during reverse flow, as described in Figure 13, the blow-down rate increases as the volume decreased, and the aeroelasticity of which needs to be further investigated.

CONCLUSIONS

The analytical method provides guidance on the property and design of compressors from the perspective of physical mechanism and is highly valuable for theoretical and practical applications. However, due to excessive ideal assumptions and simplifications, high reliance on empirical corrections, and insufficient description of the internal flow field of the compressor, most of these model can only provide qualitative conclusions but not quantatitive results.

Regarding the CFD methods, author suggestes that the body force based on experimental corrections or CFD simulations has high potential for compressor performance prediction. This method has the advantage of low computational cost and fast calculation while maintains considerable accuracy. The high fidelity RANS/URANS computations will become more and more important in terms of mechanism study and detailed flow field investigation of surge.

ACKNOWLEDGMENTS

The authors are grateful for the support of the support of the National Natural Science Foundation of China with Project No. 51636001, No. 51727810 and No. 51922098, and the National Science and Technology Major Project (2017-II-0004-0017, 2017-II-0005-0018).

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