Improvement of Parallel Compressor Model in Dealing Outlet Unequal Pressure Distribution

Kewei Xu, Jens Friedrich, Kevin Dwinger, Wei Fan, Xijin Zhang

Abstract—Parallel Compressor Model (PCM) is a simplified approach to predict compressor performance with inlet distortions. In PCM calculation, it is assumed that the sub-compressors' outlet static pressure is uniform and therefore simplifies PCM calculation procedure. However, if the compressor's outlet duct is not long and straight, such assumption frequently induces error ranging from 10% to 15%. This paper provides a revised calculation method of PCM that can correct the error. The revised method employs energy equation, momentum equation and continuity equation to acquire needed parameters and replace the equal static pressure assumption. Based on the revised method, PCM is applied on two compression system with different blades types. The predictions of their performance in non-uniform inlet conditions are yielded through the revised calculation method and are employed to evaluate the method's efficiency. Validating the results by experimental data, it is found that although little deviation occurs, calculated result agrees well with experiment data whose error ranges from 0.1% to 3%. Therefore, this proves the revised calculation method of PCM possesses great advantages in predicting the performance of the distorted compressor with limited exhaust duct.

Keywords—Parallel Compressor Model (PCM), Revised Calculation Method, Inlet Distortion, Outlet Unequal Pressure Distribution.

I. INTRODUCTION

THE concept of Parallel Compressor Model was first introduced in 1959 by Pearson and Mackenzie [1] to carry out the analysis of circumferential distortion and its effect on compressor performance. Different from Computational Fluid Dynamics (CFD) work that are generally too complex to set up, PCM employs proper mathematic methods and defines certain boundary conditions to reduce calculation cost and produce relatively reliable result as well. It is especially effective in understanding basic physics of non-uniform flow effect [2]. After PCM was purposed, extensive works have been donated to improve its accuracy. Korn [3] introduced stall delay concept to the PCM calculation in predicting stall limit. He used $S\theta$ the factor that represents compressor sensitivity to circumferential distortion in the calculation. And consequently, the prediction of stall limit has been significantly improved. To evaluate circumferential flow, Kimzey [4] developed orifice flow analogy. He considered high and low pressure region as reservoirs and the gap between stator and rotor as orifice. The

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flow is derived from the high pressure reservoirs to the low pressure reservoirs through the orifice. Therefore, the amount of flow can be calculated based on the concepts of classic orifice flow. In 1977, Mazzawy [5] employed multi-segments parallel compressor model to carry out the analysis of nonsteady and two-dimensional flow effects on blades performance. Significant improvements have been made in the calculation of distortion attenuation and circumferential flow distribution. Reid [6] developed critical inlet angle theory that is considering the most pressure ratio loss at stall conditions will happen when distorted circumferential extend equals to critical angle. He also concluded that the compressor starts to respond to inlet distortion in an instantaneous manner at the critical inlet angle and this in turn improves PCM accuracy for small circumferential distortion extent.

Above all, improvements have been made to PCM in dealing with stall limit prediction, circumferential flow effects. Moreover, critical angle theory and multi-segments concepts have been developed to optimize Parallel Compressor Model. However, little attention has been paid on dealing with outlet static pressure unequal distribution. In the duct that is not long and straight, assuming the same outlet static pressure of sub-compressors leads to tremendous error. This paper provides a revised calculation method of PCM that can correct the error. The revised method employs energy equation, momentum equation and continuity equation to acquire needed parameters and replace the equal static pressure assumption.

II. MATHEMATIC METHOD

The general calculation procedure described in this paper follows the basic concepts of simple and classical Parallel Compressor Model and the works of [7]-[9] are also referred. As it is shown in Fig. 1, a compressor is divided into three parts: compressor inlet, sub-compressors and compressor outlet. Plane 0 and plane 3 express the whole compressor's inlet and outlet, while plane 1 and 2 are sub-compressors' inlet and outlet planes. For the parameters, subscripts 1 and 2 are compressor inlet and outlet. Subscripts 11 and 21 are undistorted sub-compressors' inlet and outlet, while subscripts 12 and 22 depicts distorted sub-compressor's inlet and outlet values respectively. The calculation procedure is therefore considered as three steps based on the three parts.

In the first step, inlet parameters of sub-compressors are calculated from the separation process that compressor inlet flow becomes two streams of flow and enters sub-compressors respectively. Then, sub-compressors' performance are acquired from the combination of their inlet conditions with uniform (referenced) compressor map. At last, compressor outlet

parameters are obtained from the mixing process of sub-compressor's outlet flow. In this way, the distorted

compressor performance can be acquired. Details of calculation procedure are shown in the flow chart of Fig. 2.
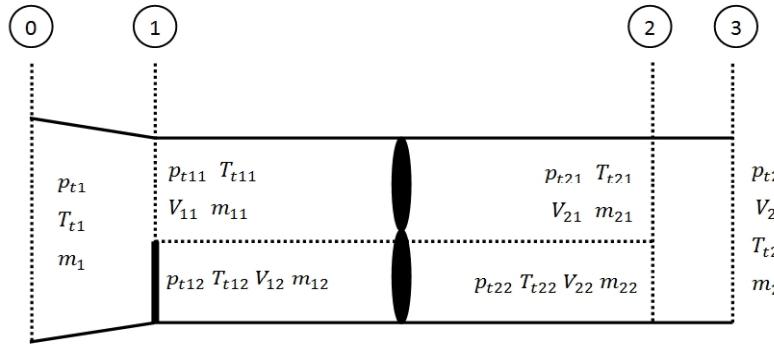

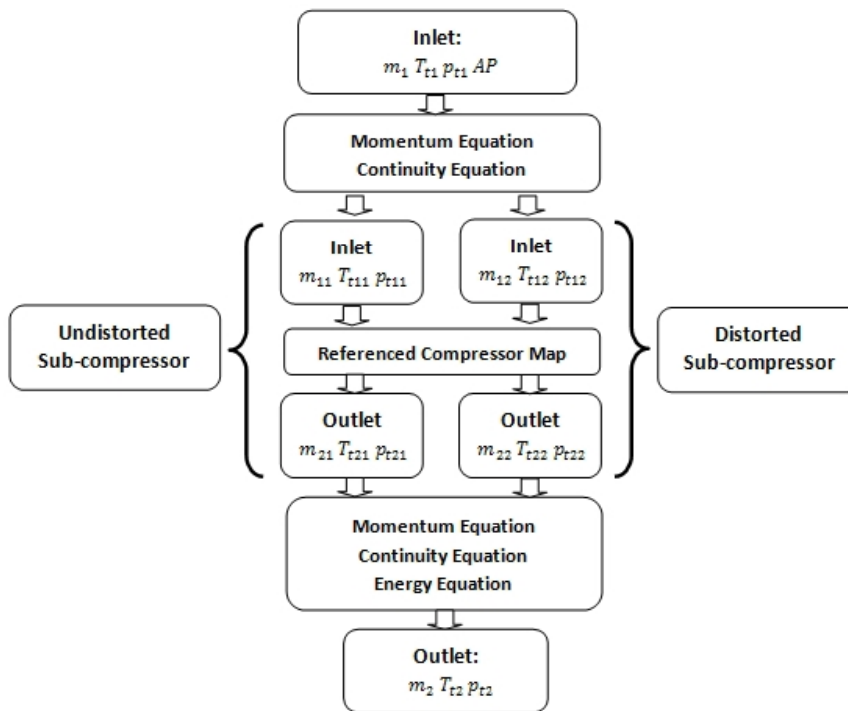Fig. 1 Schematic of PCM calculation procedure

Fig. 2 Flow chart of calculation procedure

To improve the model's accuracy, the last step of calculation procedure is revised. In the last step where sub-compressor's outlet flow is mixed into one stream, outlet conditions of the mixed flow are not acquired from the set of equal static pressure distribution but are obtained from solving of the following system of equations.

Energy equation:

$$m_2 h(T_{t2}) = (AP) m_{22} h(T_{t22}) + (1-AP) m_{21} h(T_{t21}) \qquad (1)$$

Continuity equation:

$$m_2 V_2 = (AP) m_{22} + (1-AP) m_{21} \qquad (2)$$

Momentum equation:

$$m_2 V_2 + p_{s2} A_2 = (AP) m_{22} V_{22} + p_{s22} A_{12} + (1-AP) m_{21} V_{21} + p_{s21} A_{11} \qquad (3)$$

Ideal gas equation:

$$p_t = \rho_t R T_t \qquad (4)$$

where AP is the distortion ratio, the ratio of distorted area to the whole compressor inlet area and γ is the specified heat ratio.

By defining certain boundary conditions and conditions of convergence to solve the system of equations, the

parameters of compressor outlet are obtained. As a result, the distorted compressor overall performance is predicted and the prediction proves to be valid by comparing with experiments test data.

III. RESULTS

A. Boundary Conditions

Boundary conditions include compressor inlet total pressure, total temperature and distortion ratio and distortion intensity. The total pressure and total temperature are set as sea level values. And 60 deg of compressor inlet is distorted with strong distortion, which is set according to the experiment data documented in the works of [10] and [11]. Besides, two cases of calculation are carried out based on the two types of the blades whose design point values are shown in Table I.

B. Results and Validations

The calculated results concern isentropic efficiency and pressure factor which are depicted in dashed curves and continues curves respectively. Fig. 3 presents the calculated results of Beschaufelung 7165. Blue curves are measured data of the compressor without distortions, while green lines are the measured data of the compressor with 60 deg distortions. And red curves are calculated results of distorted compressor with the same distortions.

TABLE I
TYPES OF BLADE

Blade name	φ_0 [A]	ε_0 [b]	η_0 [c]
Beschaufelung 7161	0.6	0.5	0.85
Beschaufelung 7165	0.35	0.45	0.84

a is the flow factor, which is the flow speed divided by rotor speed.
b is the pressure factor which is the ratio of isentropic work to square of rotor speed
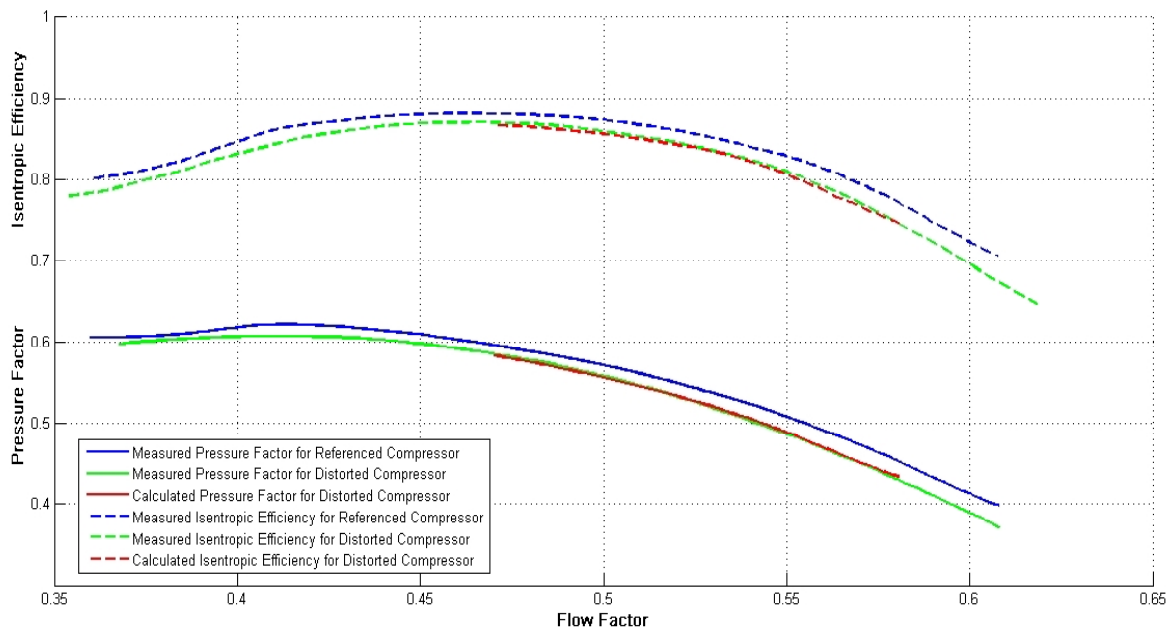c is the isentropic efficiency.

Fig. 3 Results of Beschaufelung 7165

As it is presented in Fig. 3, the calculated results including both pressure factor and isentropic efficiency agree well with experiments data, as the red curve almost overlaps with green curves. This indicates the revised calculation method is effective for prediction. Besides, another type of blade, Beschaufelung 7160 is also employed for calculation.

Fig. 4 shows little deviation between calculated results and experiment data in the high mass flow conditions, however the percentage of deviation is no more than 3% which proves the model is still valid and efficient.

Judging from the results presented below, revised calculation method of Parallel Compressor Model possesses great accuracy. The improvement of accuracy can be attributed to the approach of dealing with sub-compressors' outlet mixing process.

Because the experiment compressor's exhausted duct possesses limited length, the outlet flow of sub-compressors cannot fully have mixed and thus static pressure is not equal distributed at the outlet. In this case, acquiring compressor outlet parameters based on equal static pressure is not valid. On the contrary, solution of continuity equation, energy equation and momentum equation is sufficient to calculate such mixing process and yields proper outlet values, whose error is less than 3%. However, this degree of success is not obtained at the full working conditions of the compressor, since the distorted compressor performance at high and low mass flow conditions cannot be calculated. As it is presented, the calculated curves (red) are clearly shorter than the curves of experiment data

(green). This phenomenon is induced by the setting of compressor inlet distortion intensity.
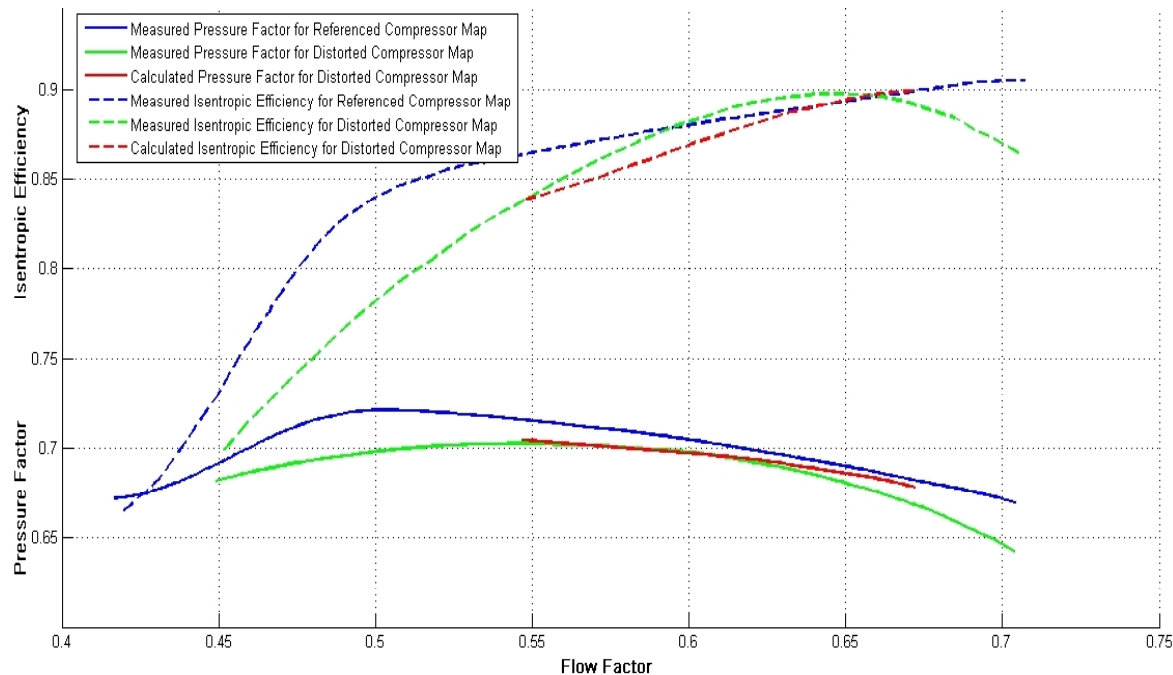

Fig. 4 Results of Beschaufelung 7161

IV. CONCLUSION

The revised method of PCM calculation procedure has been proposed and is applied on two types of blades to acquire their distorted performance. Validating the calculated results by experiment data, the excellent agreement proves the model is significant in correcting the error caused by unequal static pressure distribution. Consequently, the revised model is adequate to calculate the compressor with limited outlet duct.

ACKNOWLEDGMENT

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