A Novel Method for Developing Compressor's Characteristic Curves Due to the Guide Vane Stagger Angle Variation

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ABSTRACT

One-dimensional models of analyzing gas turbines as a whole require characteristic curves of pressure coefficient (ψ) based on flow coefficient (φ) and the characteristic curve of compressor's efficiency of stages so that compressor performance would be predicted. Variation of stagger angle of the stage's inlet guide vane stated as a geometrical variation of the stage would be resulted in the displacement of pressure coefficient characteristic curve based on the stage's flow coefficient. Performance nature of compressor stage is in a way that under this condition, the efficiency characteristic curve will remain intact. In this paper, a method would be presented to predict variations of pressure coefficient characteristic curve based on flow coefficient against variations in stagger angle of stage's guide vane so that one-dimensional modeling of axial flow compressor would be made, through characteristic curves.

Keywords: *Axial Flow Compressor, Guide Vane, Stagger Angle, Characteristic Curve, One-Dimensional Model*

Introduction

Due to the complexity of the modeling of gas turbines, one-dimensional models are very popular. A well designed one-dimensional model could monitor the detailed behavior of the gas turbines components in real-time. Such models are very effective in real-world control systems and are being used in power and electricity generation plants [1-4]. Air compressor as one of the main components of gas turbines has to be modeled in one-dimensional form, while gas turbine is being modeled as one-dimensional [5]. One of the appropriate methods of one-dimensional modeling of an axial flow compressor is using characteristic curves of each stage. In [6] a Lagrangian method was used to find the flow characteristics of an airfoil. Many of today's compressors have guide vanes with variable stagger angles [7-9]. Variations in stagger angle of guide vane including geometrical variations of the stage would be resulted in variation of the stage's characteristic curves. Theoretically, changing the stagger angle of inlet guide vane will result in variations made in characteristics curves of the stage under study [10]. Pressure coefficient (ψ) is defined as the ratio of "increase made in the stage enthalpy during the isentropic process" on "velocity mean square of vane". Coefficient of flow (φ) is defined as the ratio of the "stage's inlet axial velocity" on "mean speed of vane". Variations in characteristics curves will be in a way that characteristic curve of pressure coefficient based on the stage's coefficient of flow would be displaced. Under this condition, the efficiency characteristic curve remains fixed. This curve is defined as "value of isentropic efficiency" based on "value of pressure coefficient ratio to flow coefficient". Stagger angle effect of guide vane would be in a way that characteristic curve will move towards higher coefficients of pressures and temperature, through the more open setting of inlet guide vane to the stage (figure 1).

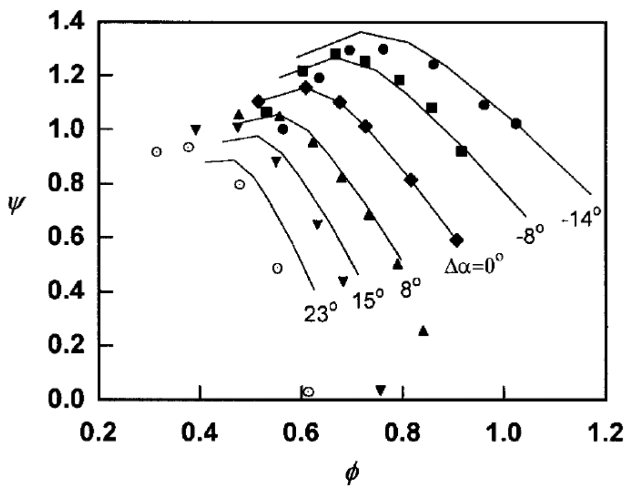

Figure 1- Variations on the characteristic curves due to variation of inlet guide vane stagger angle (positive angle variation shows guide vanes' position becoming closed) [11]

The paper aims at presenting a method through which variations in the characteristic curve of pressure coefficient based on temperature coefficient could be predicted in terms of variations in stagger angle of stage's inlet guide vane ($\Delta\alpha$). The presented method would be applied with the help of higher level calibrated models, in the one-dimensional model based on the characteristic curve. A developed one-dimensional model of the compressor would be applied in the one-dimensional model of the gas turbine.

Studying the effect of guide vane stagger angle on the characteristic curves

The capability of stagger angle variation helps more control on the performance of gas turbine under lower loads; and, having control on Surge and Stall during transient processes such as on-off, prevents them from happening. Therefore, predicting performance characteristics of the compressor's stages during one-dimensional modeling of it is of much importance, when variable geometry is used. Variable geometry causes variation in characteristic curves of pressure coefficient based on flow coefficient. So, characteristic curves have to be modified with geometrical variations. Figure (2) shows pressure coefficient characteristic curve based on flow coefficient of the first stage of IGT25 industrial compressor, prepared through drop base one-dimensional code, where inlet guide vane stagger angle is changed at design speed. More open guide vane setting would result in the displacement of the characteristic curve towards higher coefficients of pressure and flow. From variations in efficiency characteristic curve "ratio of pressure coefficient to flow coefficient" in the stage could be ignored, due to the variation made in guide vane stagger angle.

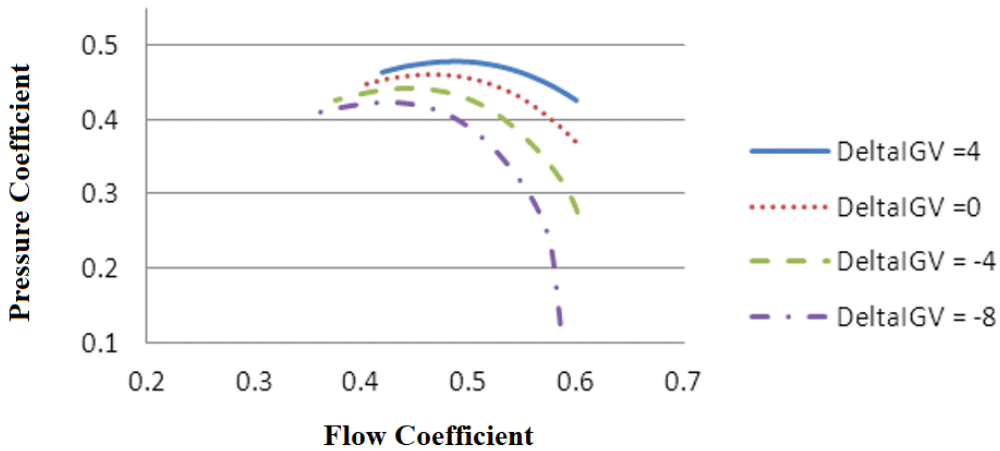

Figure 2- Effect of the inlet guide vane stagger angle variation on characteristics curve of pressure coefficient based on flow coefficient for the first stage of sample industrial compressor at the design speed (positive angle variation shows the position of guide vane to be opened)

In Figure 2, $\Delta\alpha$ is variations of stagger angle in guide vane, ψ is pressure coefficient, φ is flow coefficient, and DeltaIGV is variation levels of inlet guide vane stagger angle (IGV) in the first stage of the compressor. Variations are stated based on degree.

To develop a method for predicting displacement level of the characteristic curve of pressure coefficient based on flow coefficient, the contact angle of flow and guide vane is supposed to be almost fixed. Accordingly, efficiency would be almost fixed. As a result, relationship (1) would be established:

$$\frac{\Psi}{\varphi} = K = Constant \tag{1}$$

Using the Euler equation and velocity triangle in the stage inlet and outlet as well as a little mathematical review on relationships, the result would be as follows:

$$\frac{\psi}{\varphi} = \eta.(\frac{1}{\varphi} - \tan\alpha_1 - \tan\beta_2) \tag{2}$$

where α_1 is the absolute angle of inlet flow, β_2 is relative outlet flow angle, and η is the stage efficiency.

The ratio of axial flow velocity and relative outlet angle of rotor is a function of contact angle; and, these are fixed values if contact angle of flow and guide vane would be supposed to be fixed. Finding the derivative of relationship (2), the result would be a Equation (3):

$$d(\frac{\psi}{\varphi}) = \eta.(d(\frac{1}{\varphi}) - d(\tan\alpha_1) - d(\tan\beta_2)) = 0 \tag{3}$$

Considering fixed terms' derivatives and taking advantage of relationship (1), the following relationship would be resulted:

$$d(\frac{1}{\varphi}) = d(\tan\alpha_1) \tag{4}$$

Equation (4) shows the relation between guide vane stagger angle variation (directly specifying the value of α_1), and the coefficient of flow.

Taking advantage of equations (1) and (4), as well as mathematical rules; the changing process of coefficients of pressure and flow compared to stagger angle variations (directly equal to variations in inlet flow angle α_1) would be presented as equations (5) and (6), through discretization:

$$\phi_2 = \frac{1}{\frac{1}{\phi_1} + (\tan\alpha_2 - \tan\alpha_1)} \tag{5}$$

$$\Psi_2 = \frac{1}{\frac{1}{\Psi_1} + Correction\ Factor \times \frac{\Psi_1}{\phi_1} \times (\tan\alpha_2 - \tan\alpha_1)} \tag{6}$$

where “1” means values before curve displacement and “2” means values after displacement of diagram curve. Values of α in both relationships (5) and (6) are absolute inlet flow angle.

In equation (6), the correction factor parameter has been considered in order for the presented method to be calibrated. The parameter would be determined with the help of results obtained from 3D numerical models, and one-dimensional static model based on the base drop.

Conclusion

In some of today’s compressors and to increase the maneuverability of compressors, stages having variable guide vanes are used. Changing the stagger angle of guide vane, the characteristic curves of stages would be utilized. To develop a static one-dimensional model based on drop base, characteristic curves have to be used for prediction of compressor performance in gas turbine so that the stage’s characteristic curve displacement would be modeled. It has to be noticed that the efficiency characteristic curve will have no variation; and, it is just a pressure coefficient characteristic curve based on flow coefficient which would be prone to displacement. In the paper, a prediction method of characteristic curve variations of pressure coefficient based on flow coefficient would be presented against variations in stage guide vane stagger angle so that one-dimensional model of axial flow compressor would be made through characteristic curves. In this respect, it is supposed that stagger angle variations are in a way that contact angle remains intact. Taking advantage of velocity triangle, Euler equation, and mathematical relationships; the derivative relationship between guide vanes stagger angle variations and coefficients of pressure and flow have been obtained. Finally, for model adaptability and to reduce error, a coefficient has been considered as for model calibration, specified through results obtained from higher level models of the stage.

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