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Decoding the NGTE/Calvert Axial Flow Compressor Computer Program

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Abstract— Several models are used for the design and performance evaluation of axial compressors – thickness, clearance, efficiency and others. However, two principal models for the overall performance evaluation are used – in North America, the US National Aeronautics and Space Administration (NASA) or Steinke Model, and in Europe, the UK National Gas Turbine Establishment Model (NGTE) or Howell/Calvert Model. In all, there are essential relationships and connects in some of these models. An earlier investigator had applied the NASA model to a major UK gas turbine manufacturer's equipment with useful results. The aim of this research effort was to evaluate some of the major models, decode the NGTE Calvert computer program since some of these relationships are experimentally developed and not available in the open literature, find the connecting relationships, through new models development.

Index Terms—Axial Compressor, Axial Performance, Compressor, Compressor Performance, Compressor Tip Clearance,, Multistage Compressor, Off-Design Performance, Stage Stacking, Diffusion factors, loss coefficient, blade aspect ratio .

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1 Introduction

In the original unpublished paper, the title was given as " A Yet to be Concluded Summary Evaluation of the Calvert Program". The current title depicts more accurately, the initial steps taken to fulfill the purpose of the research effort. Given below is a brief summary of applicable relations from the Calvert program [1]. Additional relationships derived from velocity triangles and the open literature, and steps in the derivation are not shown.

2 Multiplying Factors

Based on the input data given, and by using the area data given at the sections, the mass flow correction factors, and the temperature rise mass weighted mean value correction factor, the following relations are useful in arriving at the Multiplying factors.

$$\Delta Q - MF = \frac{Q_{mean}}{0.975\Delta T_{ref}} \quad (1)$$

$$\Delta T - MF = \frac{\Delta T_{mean}}{0.99\Delta T_{ref}} \quad (2)$$

3 Blade Aspect Ratio

At Maximum Efficiency:

$$\frac{A_{R2}}{0.975A_{RM}} x \frac{h_R}{h_S} \quad (3)$$

At Stall:

$$\frac{\left(\Delta T_{mean}/0.99\Delta T_{ref}\right)^{-1} x \left(h_S/h_R\right)}{\left(A_{R1}/0.975A_{S2}\right)} \quad (4)$$

4 Reduced Design Loading

At Maximum Efficiency:

$$\left(\Delta T_{mean}/0.99\Delta T_{ref}\right)^2 x \left(A_{RM}/0.975A_{R1}\right) x \left(A_{R2}/0.975A_{R1}\right) \quad (5)$$

At Stall:

$$\frac{\left(1/8\right)\left[\left(A_{RM}/A_{R1}\right)x\left(A_{R2}/A_{R1}\right)x\left(A_{SM}/A_{R1}\right)x\left(A_{S2}/A_{R1}\right)x\left(A_{S1}/A_{RM}\right)x\left(A_{SM}/A_{RM}\right)x\left(A_{S2}/A_{RM}\right)x\left(A_{S1}/A_{R2}\right)\right]}{(0.975)} \quad (6)$$

5 Stage Effects

At Maximum Efficiency:

$$\frac{A_{S2}}{0.975A_{RM}} \quad (7)$$

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At Stall:

$$\frac{\Delta T_{mean}/0.99\Delta T_{ref}}{\left(T-MF/Q-MF\right)} \quad (8)$$

6 Modified Relationship for Diffusion Factor

$$D = 1.03 + \left[0.4 + \left(t/c\right)\right]\left[\Delta V_w / \left(s/c\right) V_1\right] + 0.7\left(t/c\right) - deH \quad (9)$$

7 FACTOR, *F*, in Howell-Calvert Relationship

By rearranging "(9)", the tangential velocity ratio in the Calvert equation (*factor f*) is easily derived:

$$\frac{\Delta V_w}{V_1} = \frac{D + deH - 0.7\left(t/c\right) - 1.03}{\left[0.4 + \left(t/c\right)\right]} . \left(s/c\right) \quad (10)$$

8 Tip Clearance

In Jack and Elder [2], a factor of 2 was missing in the clearance equation. This was an error in the derivation based on the average rather than, the addition of the hub and tip displacement thicknesses as specified in the Koch and Smith [3] paper. The corrected and modified tip clearance relation as a function of the loss coefficients in the rotor and stator is given by:

$$t_p = \frac{h}{3}\left[1 - \left\{1 - \left(\frac{\varpi_r V_1^2 + \varpi_s V_2^2}{2U\left(V_{w2} - V_{w1}\right)}\right)\left(\frac{1}{\eta}\right)\left[1 - \left(2\delta^* / h\right)\right]\right\}\right] \quad (11)$$

9 Deviation Angle

It is proposed to use the deviation angle proposed by Carter [4] as given in the Oldham [5] paper referenced in the program. An alternative deviation angle equation with improved accuracy has been proposed by Boyce [6] but complex to apply, and will take additional computing memory. It might be interesting to combine the Boyce [6] relation (since this accounts for the Mach number effects, and the thickness to chord ratio) with the factor, *m*, in the Oldham [5] relationship. The accuracy of this is yet to be verified.

The Carter rule as applied is given by:

$$\delta = m\theta\sqrt{\left(s/c\right)} \quad (12)$$

Where, *m*, is a function of the stagger angle (between 0 and 70 degrees).

$$m = 0.2162 + 0.0008595\zeta + 0.00002786\zeta^2 \quad (13)$$

10 Loss Parameter as a function of the Diffusion Factor

$$L = 0.02224 - 0.02436D + 0.05D^2 \quad (14)$$

"(14)" applies for, D>0.244
For D<0.244, loss parameter is held constant, and, L = 0.0193.

11 Loss Coefficient

Stator:

$$\varpi_s = \left[\frac{2.L}{\left(s/c\right)\cos\alpha}\right] \quad (15)$$

Rotor:

$$\varpi_r = \left[\frac{2.L}{\left(s/c\right)\left(\cos\alpha_2 / \cos\alpha_1\right)^2}\right] \quad (16)$$

Where, *L*, is the loss parameter.

12 Closing

It has not been possible to arrive at the exact values in some of the figures in the output as displayed in the Calvert program's [1] Sample Printer Results Sheets 1 and 2. Furthermore, in Sample Sheet 2, the correction for mass flow rate has probably been done with a specific heat ratio of "γ=1.0". If this is an error in the program, the actual corrected mass flow is 15 percent above its true value. How this affects the overall results is yet to be determined.

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NOTATION

P	Pressure
T	Temperature
V	Velocity
A	Area
Q	Flow rate
h	Aspect ratio
t	Blade thickness
t_p	Tip clearance
s	spacing
D	Diffusion
c	Chord
L	Loss parameter
f	factor
deH	de Haller number

Greek Letters

ϖ	Loss coefficient
α	air angle
β	Blade angle
δ	deviation
δ*	Displacement thickness

Subscripts

s	stator
r	rotor
1	inlet
2	outlet
SM	mean stator
RM	mean rotor

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