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Modeling of Compressor Performance Deterioration Due to Erosion*

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This paper presents the results of a simulation of compressor performance deterioration due to blade erosion. The simulation at both design and off-design conditions is based on a mean line row by row model, which incorporates the effects of blade roughness and tip clearance. The results indicate a pronounced effect of blade erosion on the compressor adiabatic efficiency and a lesser effect on the pressure ratio. The loss in performance is mainly caused by the increased blade surface roughness and was highest at 100% speed.

Keywords: Compressor, Performance deterioration, Simulation, Erosion, Roughness

INTRODUCTION

Aircraft engines are often exposed to ingestion of sand or runway gravel, causing the erosion of fan and compressor blades. This leads to increased blade surface roughness and tip clearances with a subsequent degradation in performance [Hamed, Tabakoff and Wenglarz (1988), Tabakoff (1988)]. In addition severe erosion damage can change the blade leading edge characteristics and reduce the blade chord, which can further deteriorate the performance [Balan and Tabakoff (1983, 1984), and Batcho, Moller, Padova and Dunn (1987)].

Several investigators have developed performance deterioration models for compressors based on the "stage stacking" method. In this approach changes were introduced in the individual compressor stage characteristics to reflect the effects of erosion [Batcho, Moller, Padova and Dunn (1987), Tabakoff, Lakshminarasimha and Pasin (1990)], and fouling [Muir, Saravanamutto and Marshall (1989), Aker and Saravanamutto (1989)] on the stage pressure, work and efficiency. Using thin airfoil theory, Batcho et al. [1987] modeled the reduction in a compressor stage pressure ratio due to the increased tip clearance and reduced chord caused by erosion, and compared their predictions with experimental results for dust eroded aircraft gas turbine engine. Tabakoff et al. [1990] modified the model by including the effects of increased surface roughness due to erosion and compared their predictions with experimental results in a single stage compressor. The model over predicted the performance deterioration due to erosion. They

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then applied the model to the multistage J-85 compressor by modifying the individual stage characteristics of Milner et al. (1975) to include the effects of chord reduction due to erosion. The results showed that erosion caused both pressure and mass flow rate to decrease, this reduction was found to be a function of both the compressor speed as well as the location of the stage where erosion occurred.

In general, the individual stage characteristic curves which are required in the "stage stacking" method are not available in the open literature. Therefore in the present investigation, a mean line method was developed to model the effects of erosion on compressor performance. Mean line methods are based on resolution of velocity triangles for each blade row and the application of loss correlations to establish the pressure and temperature rises through the stage [Casey (1987), Miller and Wasdell (1987)]. In the present investigation the effects of increased surface roughness and tip clearance due to erosion are introduced into the loss model. This model could generally be applied to predict the compressor stage performance, given the blade inlet and exit metal angles, blade stagger, camber, chord, solidity, thickness to chord ratio, and hub and tip diameters.

MODEL DESCRIPTION

The mean line performance model is based on the use of empirical correlation's for the incidence and deviation angles and pressure losses, which are separated into, profile, annulus, secondary and tip clearance losses [Casey (1987), Miller and Wasdell (1987)]. In the present study the NASA SP-36 [Johnsen and Bullock (1965)] correlation is used for incidence angle and Carter's model [Horlock (1973)] is used to calculate the flow deviation angle. The loss model developed by Koch and Smith [Koch and Smith (1976)] is used for design point operation, whereas Swan's method [Swan (1961)] is used for off-design loss predictions. It is assumed that the secondary losses are not affected by erosion and are given by following equation [Horlock (1973)]:

$$\omega_s = (0.072/\sigma)(\cos^2\beta_2/\cos\beta_m)(\tan\beta_2 - \tan\beta_1)^2. \tag{1}$$

EFFECT OF INCREASED SURFACE ROUGHNESS

Balan and Tabakoff [Balan and Tabakoff (1983, 1984)] conducted an experimental study in which they measured compressor cascades and single stage compressor performance after various amounts of sand were ingested. Both the cascade and compressor performance deteriorated with increased sand ingestion. They attributed the loss of performance to the following changes, which were characterized in their reported results:

1. Increased blade surface roughness.
2. Increased blade tip clearance.
3. Blunting of blade leading edges.
4. Thinning of the trailing edge and shortening of the chord.

The experimental results of Balan and Tabakoff (1983, 1984) indicated an initial sharp rise in cascade losses with increased sand mass ingestion up to 0.10 Kg/cm^2, then the losses remained practically unchanged up to a sand mass ingestion of 0.32 Kg/cm^2, before increasing sharply again. The latter increase in losses was attributed to the blunting of the blade leading edge and shortening of the blade chord. The initial rise in loss coefficient was attributed to the movement of the transition point towards the leading edge, with increased surface roughness. The levels of blade erosion considered in the present investigation are within that range. Two levels of roughness representative of those observed in the experimental work of Balan and Tabakoff (1984) were simulated.

CASE A: Moderate erosion. Rotor and stator surface roughness, $R_a = 4.0\,\mu m$.

CASE B: Higher erosion, with transition point at minimum distance from the leading edge. Rotor roughness, $R_a = 8.0\,\mu m$, stator roughness, $R_a = 6.0\,\mu m$.

The following correlation for drag on a fully rough flat plate [Mills and Hang (1983)] was used to model the effects of increased surface roughness in the calculation of the profile losses due to the boundary layer development on the blade surface.

$$C_d = (2.625 - 0.618\log_e(k_s/c))^{-2.57}. \qquad (2)$$

The equivalent sand grain roughness, k_s was taken to be equal to 6.2 times the center line average roughness [Koch and Smith (1976)], and the center line average surface roughness of smooth blades was taken as $R_a = 0.371\ \mu m$ [Kramer and Smith (1978)]. The contribution of the surface roughness to the profile loss is calculated from the following relation:

$$\omega = C_d\sigma(\cos\beta_1)^2/(\cos\beta_m)^3. \qquad (3)$$

EFFECT OF INCREASED TIP CLEARANCE

The loss in efficiency due to increased tip clearance is modeled using the empirical correlation of Lakshminarayana (1970).

$$\Delta\eta = (1.4\,\Delta t\,\Psi/h)/(\cos\beta_m) \times \{1 + 10[(\phi\Delta t/c)/(2\Psi\cos\beta_m)]^{0.5}\}. \qquad (4)$$

The increase in the rotor tip clearance due to erosion was taken to be equal to 1% of the blade height based on the experimental data of Balan and Tabakoff (1984).

In the model, the flow conditions at the blade row exit are iterated from the assumption of an initial exit axial velocity and the upgraded loss calculations. The exit conditions of each blade row constitute the input conditions to the next blade row.

RESULTS AND DISCUSSIONS

The compressor performance simulation were performed for a single stage axial compressor with NACA 65 airfoils. The performance parameters for stage 23B-20 of Britsch et al. (1979) are listed below:

Speed : 9,170 rpm
Pressure Ratio : 1.252
Mass Flow : 9.475 kg/s
Tip Speed : 243.9 m/s
Hub-Tip Ratio : 0.8
Aspect Ratio : 1.0
Rotor Diffusion Factor : 0.44

Figures 1 and 2 compare the computed results for smooth blades at three different speeds (N = 100%, 90% and 70% (design speed)), to the

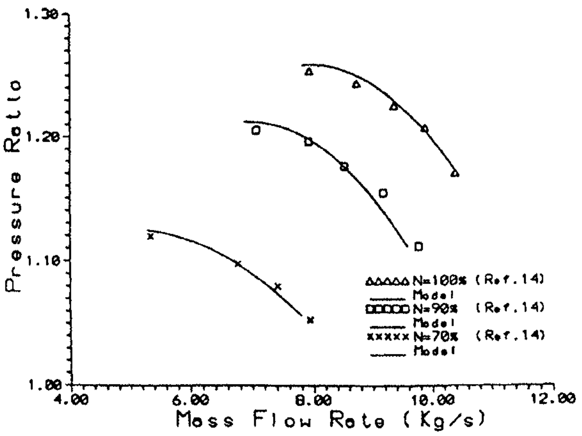

FIGURE 1 Comparison of predicted pressure ratio with actual test results.

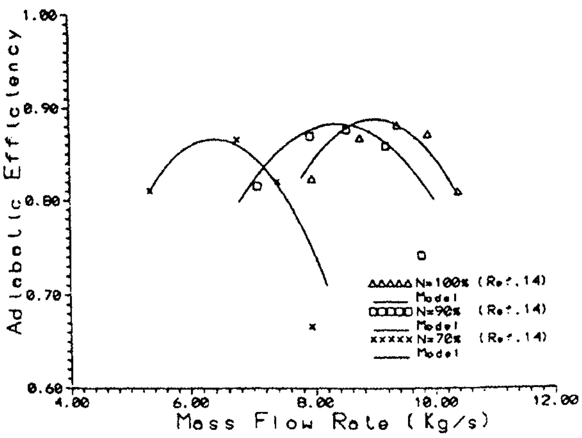

FIGURE 2 Comparison of predicted adiabatic efficiency with actual test results.

experimental values. The qualitative agreement between the model and the experimental values is quite good at all speeds.

Figure 3 shows the effects of increasing blade surface roughness on the stage pressure ratio. The model predicts a small drop in the pressure ratio at 100% and 90% speeds that diminishes at 70% speed. Figures 4 and 5 are expanded views of the pressure ratio plotted against the mass flow rate for 100% and 90% speeds. As seen in both these figures the loss in pressure ratio increases with increased mass flow and can reach 0.5% in the case of surface roughness corresponding to moderate erosion (case A). Figures 6 and 7 present the effect of surface roughness on adiabatic efficiency. One can see that the roughess has a far greater effect on

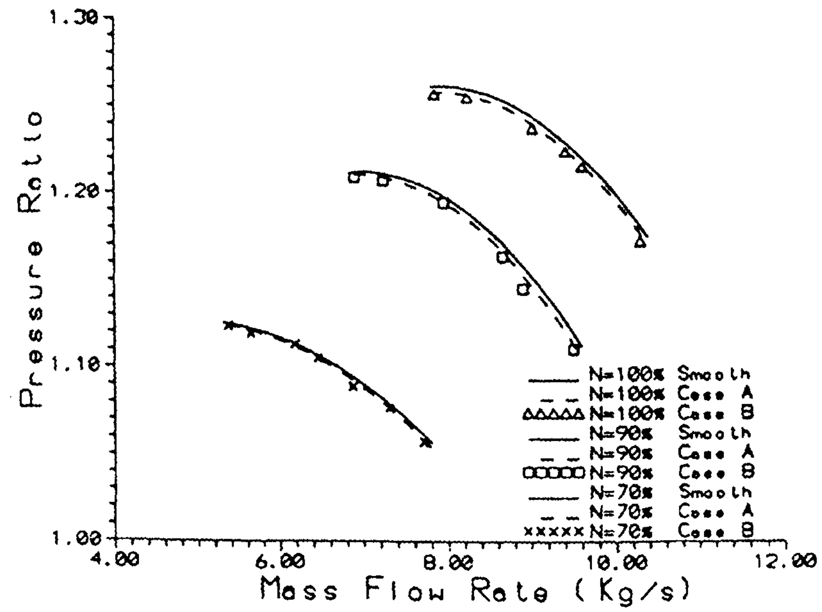

FIGURE 3 Effect of surface roughness on pressure ratio.

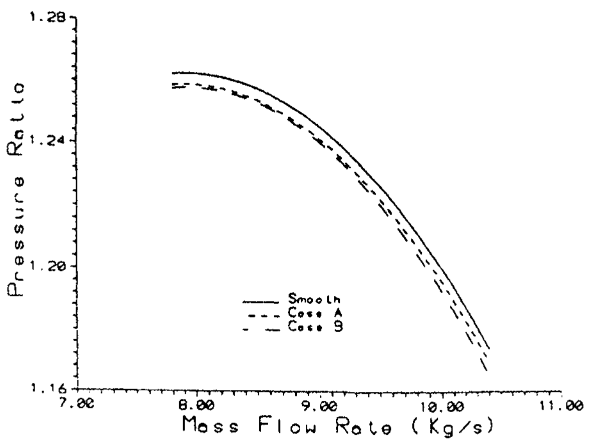

FIGURE 4 Effect of surface roughness on pressure ratio, N = 100%.

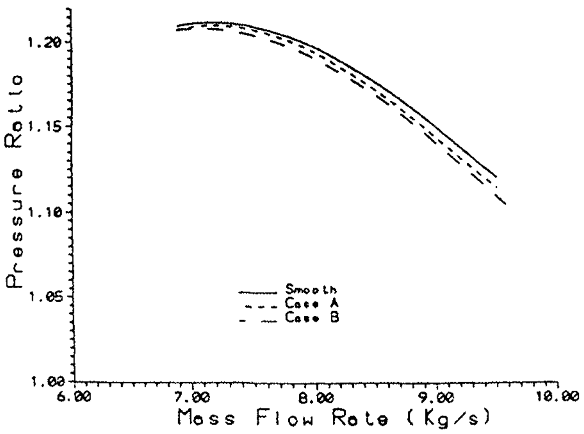

FIGURE 5 Effect of surface roughness on pressure ratio, N = 90%.

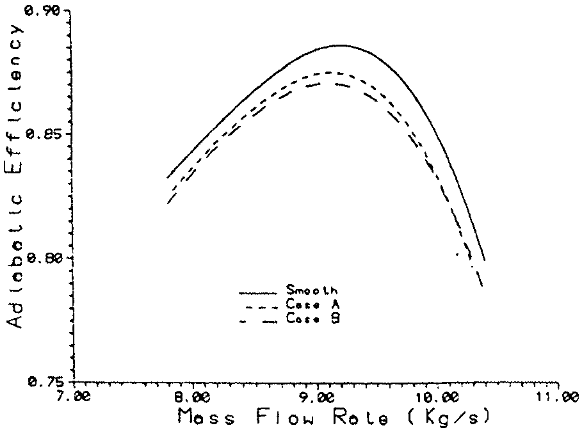

FIGURE 6 Effect of surface roughness on adiabatic efficiency, N = 100%.

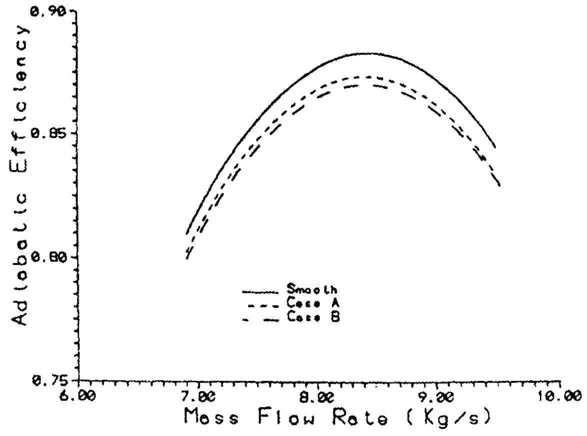

FIGURE 7 Effect of surface roughness on adiabatic efficiency, N = 90%.

the adiabatic efficiency compared to the pressure ratio. The drop in adiabatic efficiency, due to increased blade roughness, caused by moderate erosion (case A) is approximately 2% at both 100% and 90% speeds. The drop in the pressure ratio and adiabatic efficiency is small in going from the roughness Case A to Case B. This is in agreement with the experimental results of Balan and Tabakoff (1984).

The combined effects of increased blade tip clearance and surface roughness (case A) due to erosion, on the compressor performance at 100% speed, are presented in Figs. 8 and 9. One can observe

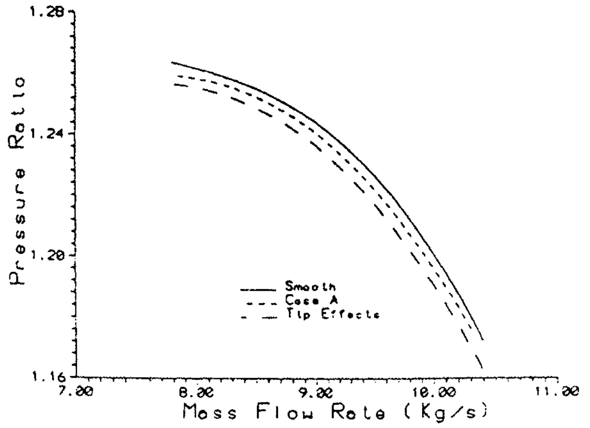

FIGURE 8 Combined effects of surface roughness and tip erosion on pressure ratio, N = 100%.

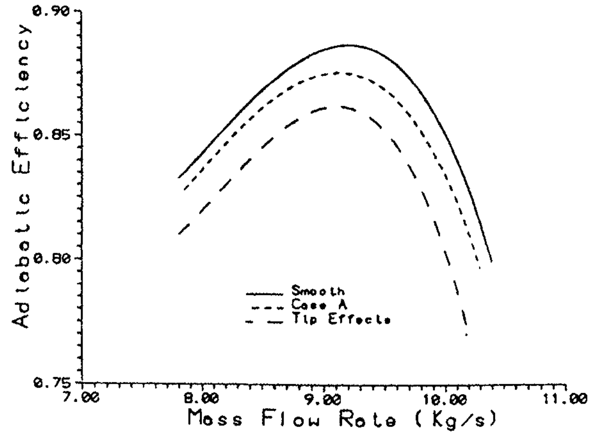

FIGURE 9 Combined effects of surface roughness and tip erosion on adiabatic efficiency, N = 100%.

a slight reduction in the compressor pressure ratio due to the additional effect of tip clearance. However the increased tip clearance due to erosion has a more pronounced effect on the stage adiabatic efficiency with an additional 1.5 to 2% drop over the operating range.

CONCLUSIONS

A mean line compressor performance model was developed to predict the change in compressor performance associated with blade erosion by ingested particles. It was validated for uneroded single stage compressor through comparison with experimental data and then applied to predict the effects of increased surface roughness and tip clearance on compressor pressure ratio and adiabatic efficiency. The model predicted a more pronounced reduction in compressor efficiency compared to the pressure ratio. A loss in adiabatic efficiency of 3–4% was predicted under the combined effects of increased blade surface roughness and tip clearance due to erosion.

NOMENCLATURE

c = blade chord
C_d = coefficient of drag
h = blade height
k_s = equivalent sand grain roughness
R_a = center line average roughness
t = tip clearance
β = blade angles
φ = flow coefficient
η = efficiency
σ = blade solidity
ω = loss coefficient
ψ = work coefficient

Subscripts

1 = inlet
2 = outlet
m = mean
s = secondary

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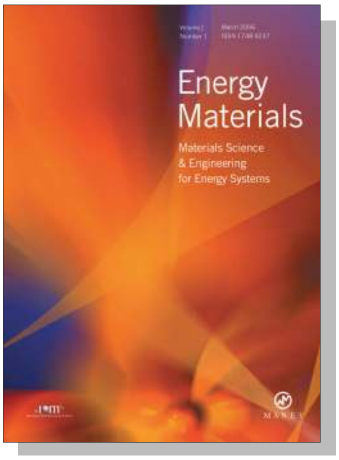

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