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BREAK

SIMULATION OF PERFORMANCE DETERIORATION IN ERODED COMPRESSORS

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ABSTRACT

A simple model was developed to simulate axial flow 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 that the increased roughness reduces the pressure ratio as well as the adiabatic efficiency of the compressor at all speeds with the largest influence at 100% speed. Increased tip clearance has a more pronounced effect on the compressor adiabatic efficiency and a lesser effect on the pressure ratio. According to the obtained results the loss in compressor performance due to erosion increases with increased blade loading.

NOMENCLATURE

c	chord
C_d	coefficient of drag
D_{eq}	equivalent diffusion ratio
h	blade height
k_s	equivalent sand grain roughness
m	deviation correlation constant
N	speed, rpm
R_a	centerline average roughness
s	pitch
t	tip clearance
β_m	mean blade angles
δ	deviation
θ	momentum thickness
ϕ	flow coefficient
ϕ'	blade chamber
η	efficiency
ψ	work coefficient

INTRODUCTION

The ingestion of sand into aircraft engines can result in a temporary loss of power as well as a permanent damage to the engine, Hamed et. al. (1988) and Tabakoff (1988). The permanent loss of aerodynamic performance is mainly associated with the erosion of the fan and compressor blades and to a lesser extent other engine components. In addition to the change in aerodynamic performance, severe erosion can lead to mechanical vibration due to imbalance in the rotating components.

Kramer and Smith (1978) and Richardson et. al. (1979) have studied the effects of in service performance degradation of CF6 and JT9 compressors. It was found that pitting and dirt build up increased the surface roughness and the thickness of the compressor blades. Measurements performed on these pitted blades showed that the surface roughness had increased from 0.371 μm to 2.04 μm. Richardson et. al. (1979) calculated that this increase in surface roughness caused a 0.22 point drop in the efficiency.

Balan and Tabakoff (1984) and Tabakoff and Balan (1982) have conducted experimental studies in which they measured the performance deterioration in a single stage compressor and in compressor cascades after various amounts

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of sand were ingested. The performance deterioration of both cascade and compressor were found to increase with increased sand ingestion. The experimental results indicated an initial sharp rise in cascade losses with increased sand mass ingestion up to 0.10 Kg/cm^2, then the losses increased at a lower rate up to a sand mass ingestion of 0.32 Kg/cm^2, before increasing sharply again. The initial rise in the loss coefficient was attributed to the movement of the transition point towards the leading edge, with increased surface roughness. The latter increase in the losses was attributed to blunting of the blade leading edge, shortening of the blade chord and the separation of the boundary layer.

From these and other experimental studies by Batcho et. al. (1987) and Dunn et. al. (1987), (1994), the loss of compressor performance due to sand, dust and ash ingestion is attributed to the following:

1. Increased blade surface roughness
2. Increased blade tip clearance
3. Blunting of blade leading edges
4. Shortening of the chord

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 was found to slightly under predict the uneroded compressor performance and over predict the performance deterioration due to erosion.

Recently Suder et. al. (1994) conducted a detailed experimental study into the effects of adding thickness and roughness to a transonic compressor rotor. They tested different coating configurations over 10%, 50% and 100% of the blade chord. From their measurements at 60%, 80 % and 100% of design speed. They concluded that thickness/ roughness increase over the first 10% of the blade chord accounts for virtually all of the performance degradation for smooth coating (increase in blade thickness only and no increase in the surface roughness), compared to about 70% of the observed performance degradation for the rough coating. They also determined that roughness had a significant effect on the blade boundary layer in the subsonic case at 60% design speed, resulting in a 1-3 points loss in adiabatic efficiency.

Tabakoff et. al. (1990) and Lakshminarasimha et al. (1994) used the stage stacking method to determine the performance deterioration in multistage compressors associated with increased blade roughness and decrease in the blade chord. These models, require compressor stage maps which are considered proprietary secrets by gas turbine manufacturers and are typically not available in the open literature.

In the present investigation, a simple mean line method was used to model the effects of increased blade roughness and tip clearance due to erosion, on compressor performance. The model developed can predict the compressor stage performance, given the blade inlet and exit metal angles, blade stagger, camber, chord, solidity, thickness to chord ratio and hub to tip diameters. Predicted results for the total pressure ratio and adiabatic efficiency are presented and compared with experimental results for three different compressors.

MODEL DESCRIPTION

The mean line method is based on resolution of velocity triangles for each blade row and application of correlation's for flow deviation angles and various flow losses, (profile, shock, end wall and tip clearance), to establish the pressure and temperature rises through the compressor stage, (Casey (1987) and Miller and Wasdell (1987)). In the present investigation, the simple model developed for eroded compressor performance deterioration includes the effects of the increase in the profile loss due to increased surface roughness and the decrease in efficiency due to increased tip gap. The correlation's for losses, incidence and deviation angles are summarized in the following subsection.

Profile, Shock and End wall Losses

The design point profile and shock losses are calculated using Koch and Smith's (1976) model. The wake momentum thickness used in the profile loss calculation is based upon Starke's (1981) correlation.

$$(\theta/c) = 0.0045 / (1 - 0.95 \log_e (D_{eq}))$$

This correlation was proposed to better predict the losses at high diffusion levels, which were over predicted by the original Lieblein equations. The off design profile losses are modeled using Swan's (1961) equations. A simple model as suggested by Cumptsy (1989) is used in the prediction of blockage or end wall loss. Blockage is assumed to be 0.5 per cent per each blade row up to a maximum of 4 per cent.

The design incidence is calculated using the equations given by Johnsen and Bullock (1965). The flow deviation is calculated using Miller and Wasdell's (1987) modified form of Carter's rule. The equation which has been tested against in-house Rolls-Royce experimental data is as follows:

$$\delta = 1.13\ m\ (\phi' \sqrt{(s/c)} + 3)$$

Roughness Effects

The increase in profile losses due to roughness is modeled as drag correlation for fully rough plates given by Mills and Hang (1983).

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

Tip Clearance Effects

As the solid particles travel through the compressor, they acquire larger circumferential velocities from their impacts with the rotor blade and are centrifuged radially outward. The blade tip erosion results in progressively increased tip clearances from front to the rear stages in multistage compressors, (Tabakoff (1987), Dunn et. al. (1987), (1994)).

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

$$\Delta\eta = (1.4\ \Delta t\ \psi/h) / (\cos\beta_m) \{1 + 10[(\phi\ \Delta t/c) / (2\psi \cos\beta_m)]^{0.5}\}$$

RESULTS AND DISCUSSIONS

The compressor performance prediction model was developed based on the outlined procedure in the model description. The model was validated using the experimentally measured performance data of Balan and Tabakoff (1984) obtained before and after erosion caused by the ingestion of 25 kg of sand. The model was then used to predict the effects of increased blade roughness and tip clearance due to erosion in two other single stage compressors with higher blade loading, (Britsch et. al. (1979)). The three compressors are referred to as Test Cases 1, 2 and 3.

Test Case 1: Single stage, very low loading compressor with NACA 65 airfoils, (Balan (1984) and Balan and Tabakoff (1984)).

Test Case 2: Single stage, low loading compressor with NACA 65 airfoils, Stage 23B-20 of Britsch et. al. (1979).

Test Case 3: Single stage, high loading compressor with NACA 65 airfoils, Stage 28B-22 of Britsch et.al. (1979).

The Reynolds number based on rotor chord and relative inlet velocity is in the range of 1.25×10^5 to 8.18×10^5 for the three single stage compressors. The design point performance parameters for the Test Case 1 compressor is listed in Table 1, where as those of Test Cases 2 and 3 compressors are listed in Table 2.

TABLE 1: Design Characteristics of Test Case 1 Compressor

Parameters	
Pressure Ratio	1.10
Adiabatic Efficiency	0.88
Mass Flow, Kg/s	3.67
Rotational Speed, rpm	9,000
Tip Speed, m/s	83.0

TABLE 2: Design Characteristics of Test Case 2 and 3 Compressors

Parameters	Test Case 2	Test Case 3
Speed, rpm	9,170	9,170
Pressure Ratio	1.25	1.38
Mass Flow, Kg/s	9.47	9.47
Tip Speed, m/s	243.9	243.9
Hub-Tip Ratio	0.8	0.8
Aspect Ratin	1.0	0.80
Rotor Diffusion Factor	0.44	0.56

In the current investigation the equivalent sand grain roughness, k_s was taken to be equal to 6.2 times the center line average roughness, R_a as suggested by Koch and Smith (1976). Schaffler (1980) later proposed a value of 8.9 for the same parameter. The center line average roughness of smooth blades was taken as R_a = 0.371 μm, (Kramer and Smith (1978)).

The following levels of eroded blade surface roughness representative of those observed in the experimental work of Balan and Tabakoff (1984) were simulated.

Roughness A: Moderate roughness. Rotor and stator roughness, R_a = 4.0 μm

Roughness B: Higher roughness. Rotor roughness, R_a = 8.0 μm, stator roughness, R_a = 6.0 μm

The increase in rotor tip clearance due to erosion was taken to be 0.5% of the blade height for the three single stage compressors. This is based on the experimental observations of Dunn et. al. (1987), (1994) on a Pratt & Whitney J57 turbojet engine after dust and volcanic ash ingestion.

Test Case 1: Figures 1 and 2 compare the predicted results using the outlined method to the experimental results of Balan and Tabakoff (1984). Agreement between the predicted and the experimental results is quite good in the case of the uneroded compressor. According to Fig. 1 the predicted loss in pressure ratio is nearly the same for moderate roughness A and higher roughness B. On the other hand, Fig. 2 indicates that the predicted loss in efficiency increases with increased blade surface roughness, from 0.5% for moderate roughness A to about 1.2% in the case of the higher roughness B. The experimental results (Balan (1984) and Balan and Tabakoff (1984)) shown in Figs. 1 and 2 were obtained after the ingestion of 25 kg of sand. They reported more extensive physical damage to the blades at these high levels of sand ingestion beyond increased surface roughness and tip clearance. The reported shortening of the chord, blunting of the leading edge and thinning of the trailing edge, can account for the additional performance losses, which are not modeled in the current investigation.

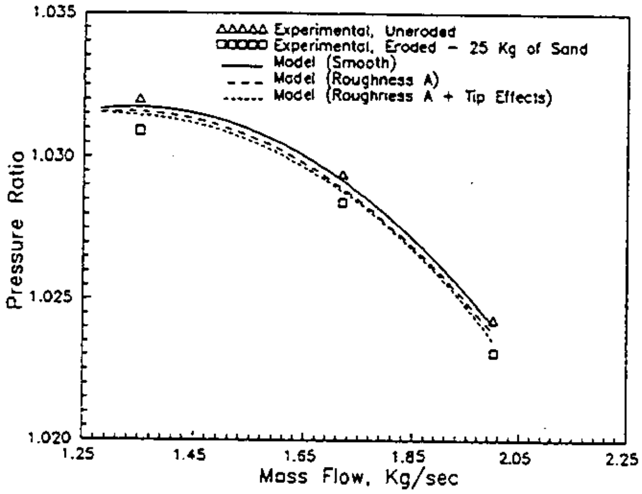

Figure 1 Comparison of Predicted Pressure Ratio With Experimental Results for Test Case 1.

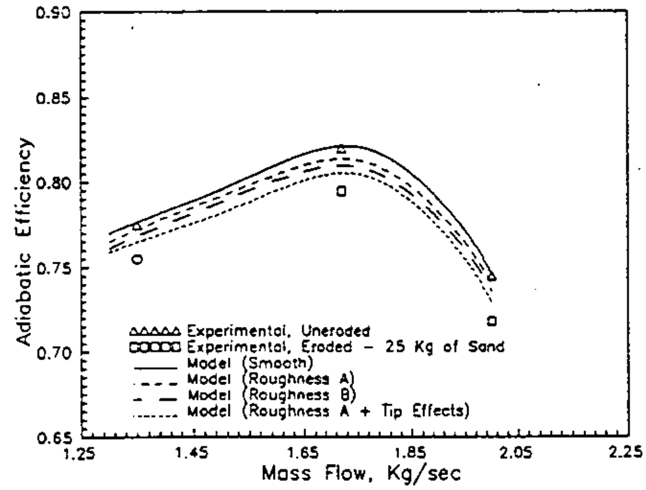

Figure 2 Comparison of Predicted Adiabatic Eficiency With Experimental Results for Test Case 1.

Test Case 2: Figures 3 through 6 present the computed results for the single stage compressor 23B-20. According to Fig. 3 which presents the results for uneroded blades the qualitative agreement between the model and the experimental values (Britsch et. al. (1979)) is quite good at all speeds (N=100%, 90% and 70%). Fig. 4 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. Figure 5 is an expanded view of the pressure ratio and the adiabatic efficiency plotted against the mass flow rate for 100% speed.

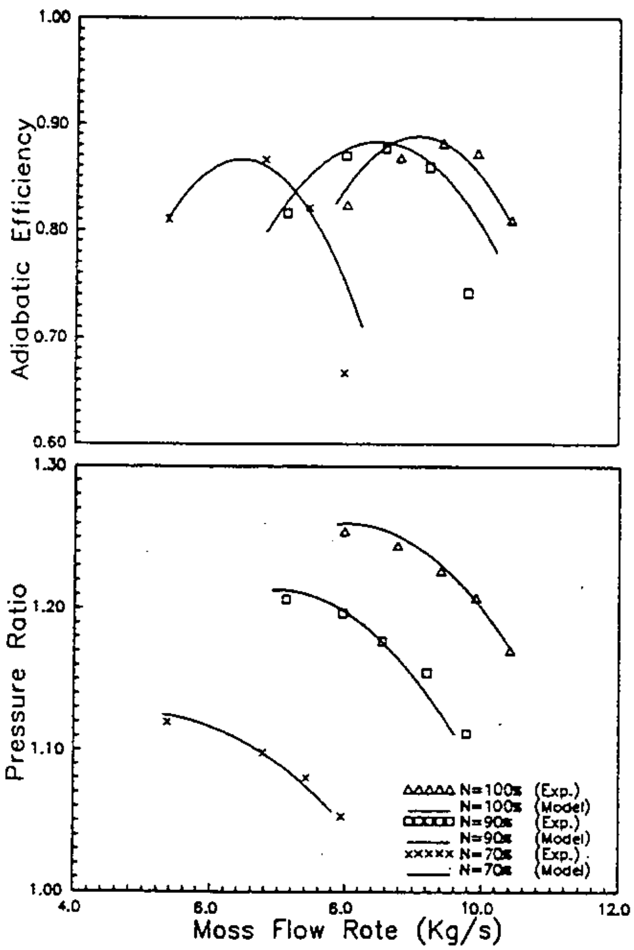

Figure 3 Comparison of Predicted and Experimental Results for Uneroded Blades of Test Case 2.

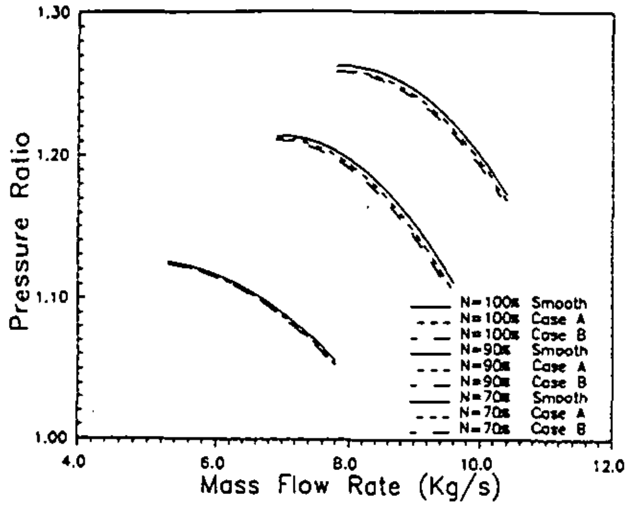

Figure 4 Effect of Surface Roughness on Pressure Ratio for Test Case 2.

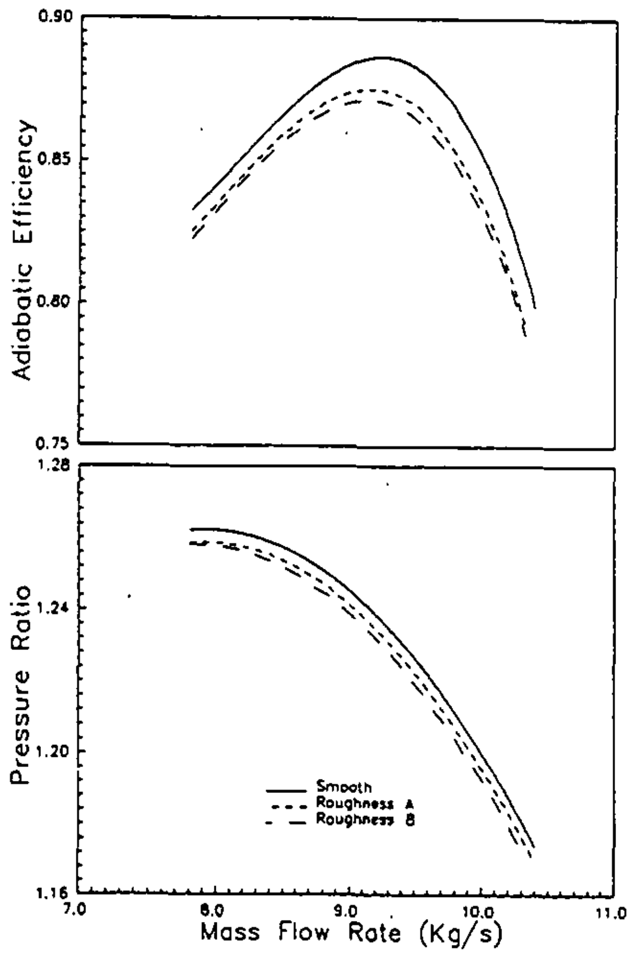

Figure 5 Effect of Surface Roughness on Compressor Performance at N=100% for Test Case 2.

As seen in the figure the loss in pressure ratio increases with increased mass flow and can reach 0.5% in the case corresponding to moderate roughness A. The drop in adiabatic efficiency, due to increased blade roughness, is approximately 2% at 100 % speed and at peak efficiency. This is nearly four times the reduction reported in test case 1, which were obtained at 55% design speed. Higher roughness B causes additional small reductions in the pressure ratio and adiabatic efficiency.

The combined effects of increased tip clearance due to erosion and moderate roughness A at N=100% is shown in Fig. 6. Increased tip clearance is predicted to have a more pronounced effect on the stage adiabatic efficiency with an additional 2 to 2.5% drop over the operating range. Comparing the results with test case 1, one can conclude that the loss in aerodynamic performance increases with increased blade loading. This is confirmed by the additional results of test case 3 which follows.

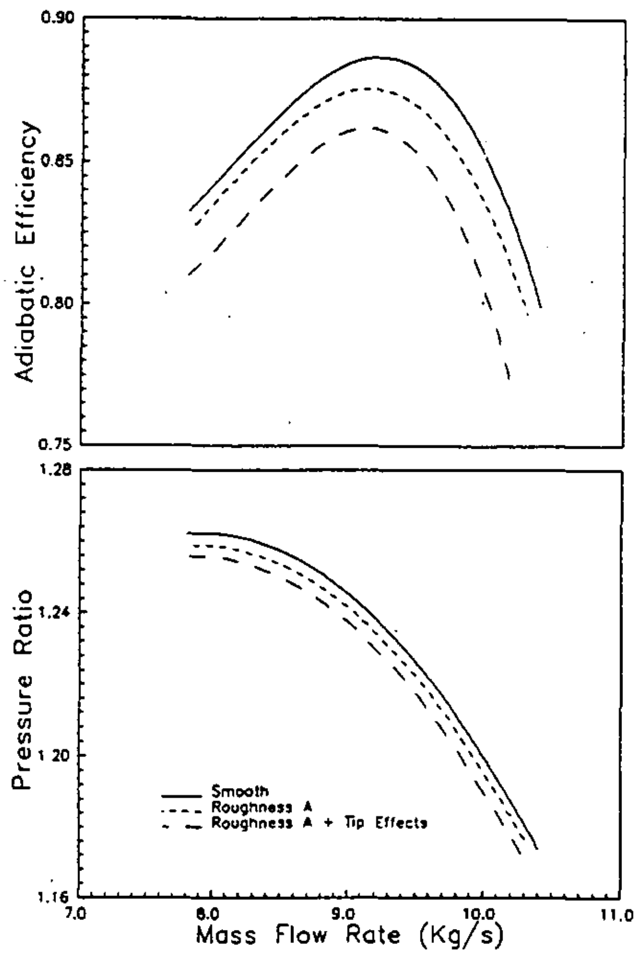

Figure 6 Combined Effects of Surface Roughness and Tip Clearance on Compressor Performance at N=100% for Test Case 2.

Test Case 3: Figures 7 and 8 present the computed results for the highly loaded single stage 28B-22 compressor. Again the agreement between the model prediction and experimental results (Britsch et. al. (1979)) for uneroded compressor is fairly good as can be seen in Fig. 7. Figure 8 shows the variation of the pressure and adiabatic efficiency with mass flow for the case of rough blades corresponding to roughness A and B at N=100%. The drop in efficiency in this case is nearly two times that of test case 2. Although not shown, the combined effects of tip erosion and moderate roughness A, exhibited similar trends to those of test case 2.

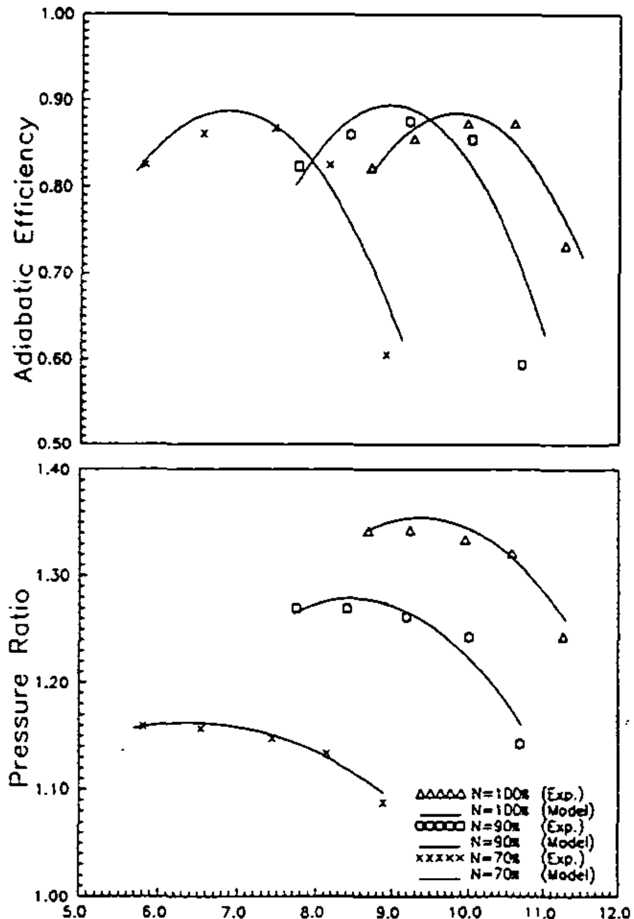

Figure 7 Comparison of Predicted and Experimental Results for Uneroded Blades of Test Case 3.

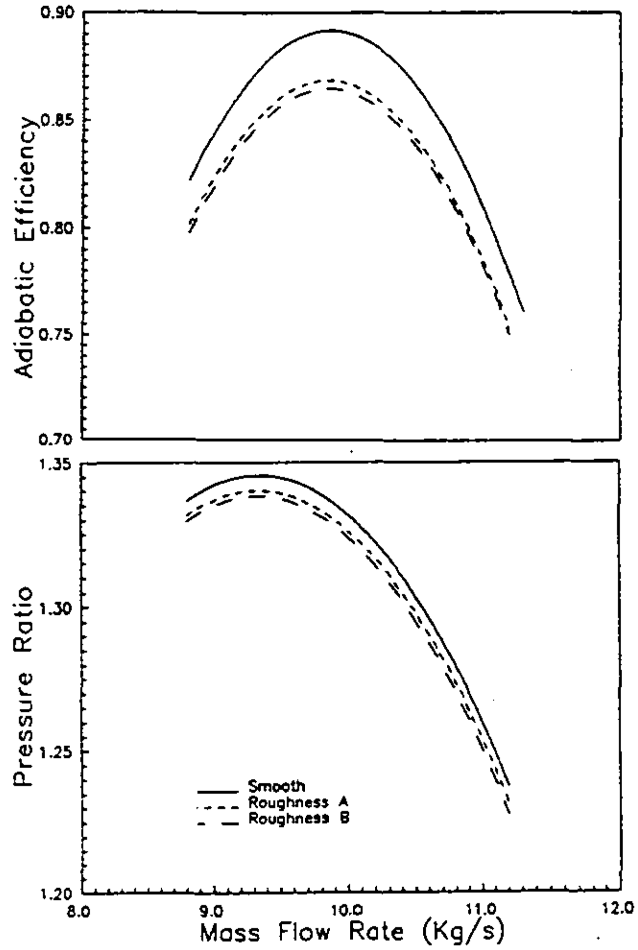

Figure 8 Effect of Surface Roughness on Compressor Performance at N=100% for Test Case 3.

CONCLUSIONS

The effects of increased blade roughness and tip clearance due to erosion are described by means of a simple mean line performance model. The model was applied to three test cases corresponding to single stage compressors with different levels of blade loading. The predictions indicate that the combined effects of increased surface roughness and tip clearance cause a pronounced reduction in stage efficiency. The reductions prevailed over the operating range but were higher at 100% speed and for highly loaded compressor stages. Comparison with experimental data indicates that the measured loss in compressor performance is greater than the predictions, and the discrepancy is attributed to the effects of blade leading edge blunting and trailing edge thinning which should be included in future models.

REFERENCES

Balan, C., 1984, "Performance Deterioration of Cascades Exposed to Solid Particles," Ph.D. Dissertation, University of Cincinnati.

Balan, C. and Tabakoff, W., 1984, "Axial Flow Compressor Performance Deterioration," AIAA Paper 84-1208.

Batcho, P.F., Moller, J.C., Padova, C. and Dunn, M.G., 1987, "Interpretation of Gas Turbine Response Due to Dust Ingestion," ASME Journal of Engineering for Gas Turbines and Power, vol. 109, pp 344-352.

Britsch, W.R., Osborn, W.M. and Laessig, M.R., 1979, "Effects of Diffusion Factor, Aspect Ratio and Solidity on Overall Performance of 14 Compressor Middle Stages," NASA TP 1523.

Casey, M.V., 1987, "Mean Line Prediction Method for Estimating the Performance Characteristic of an Axial Compressor Stage," Paper C264/87, Proc. I. Mech. E., International Conference on Turbomachinery Efficiency Prediction and Improvement, Cambridge, England.

Cumpsty, N.A., 1989, "Compressor Aerodynamics," Longman Scientific & Technical, London.

Dunn, M.G., Padova, C., Moller, J.E. and Adams, R.M., 1987, "Performance Deterioration of a Turbofan and a Turbojet Engine Upon Exposure to a Dust Environment," ASME Journal of Engineering for Gas Turbines and Power, vol. 109, pp 336-343.

Dunn, M.G., Baran, A.J. and Miatech, J., 1994, " Operation of Gas Turbine Engines in Volcanic Ash Clouds," ASME Paper 94-GT-170.

Hamed, A., Tabakoff, W. and Wenglarz, R.A., 1988, "Particulate Flows and Blade Erosion," von Karman Institute for Fluid Dynamics Lecture Series, VKI-LS-1988-08.

Johnsen, I.A. and Bullock, R.O., eds., 1965, " Aerodynamic Design of Axial Flow Compressors," Chap. 6 & 7, NASA SP-36.

Koch, C.C. and Smith, L.J., Jr, 1976, "Loss Sources and Magnitudes in Axial Flow Compressors," ASME Journal of Engineering for Power, vol. 98, pp 411-424.

Kramer, W.H. and Smith, J.J., 1978, "Long-Term CF6 Engine Performance Deterioration Evaluation of Engine S/N 451-380," NASA-CR-159390.

Lakshminarasimha, A.N., Boyce, M.P. and Meher-Homji, C.B., 1994, "Modeling and Analysis of Gas Turbine Performance Deterioration," ASME Journal of Engineering for Gas Turbine and Power, vol. 116, pp 46-52.

Lakshminarayana, B., 1970, "Methods of Predicting the Tip Clearance Effects in Axial Flow Turbomachinery," ASME Journal of Basic Engineering, vol. 92, pp 467-482.

Miller, D.C. and Wasdell, D.L., 1987, "Off-Design Prediction of Compressor Blade Losses," Paper C279/87, Proc. I. Mech. E., International Conference on Turbomachinery Efficiency Prediction and Improvement, Cambridge, England.

Mills, A.F. and Hang, X., 1983, "On the Skin Friction Coefficient for a Fully Rough Flat Plate," ASME Journal of Fluids Engineering, vol. 105, pp 364-365.

Richardson, J.H., Sallee, J.P. and Smakula, F.K., 1979, " Causes of High Pressure Compressor Deterioration In Service," AIAA Paper 79-1234.

Schaffler, A., 1980, "Experimental and Analytical Investigation of the Effects of Reynolds Number and Blade Surface Roughness on Multistage Axial Flow Compressors," ASME Journal of Engineering for Power, vol. 192, pp 5-13.

Starke, J., 1981, "The Effect of the Axial Velocity Density Ratio on the Aerodynamic Coefficients of Compressor Cascades," ASME Journal of Engineering for Power, vol. 103, pp 210-219.

Suder, K.L., Chima, R.V., Strazisar, A.J. and Roberts, W.B., 1994, "The Effects of Adding Roughness and Thickness to a Transonic Axial Compressor Rotor," ASME Paper 94-GT-339.

Swan, W.C., 1961, "A Practical Method of Predicting Transonic Compressor Performance," ASME Journal of Engineering for Power, vol. 83, pp 322-330.

Tabakoff, W., 1987, "Compressor Erosion and Performance Deterioration," ASME Journal of Fluids Engineering, vol. 109, pp 297-306.

Tabakoff, W., 1988, "Causes for Turbomachinery Performance Deterioration," ASME Paper 88-GT-294.

Tabakoff, W. and Balan, C., 1982, "Compressor Cascade Performance Deterioration Caused by Sand Ingestion," NASA-CR-168067.

Tabakoff, W., Lakshminarasimha, A.N. and Pasin, M., 1990, "Simulation of Compressor Deterioration Due to Erosion, " ASME Journal of Turbomachinery, vol. 112, pp 78-83.