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Experimental Study of the Effect of Blade Setting Errors on Stalling Performance of Cascade

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A series of tests on the effect of one-blade setting errors on the stalling performance of a compressor cascade is reported. The tests were conducted on a low speed blower tunnel and at a Reynolds number in the region of 3×10^5 (based upon blade chord and upstream averaged velocity). During all tests the axial velocity ratio of the flow was about 1.33. The incidence angle was in the stall region. The effects of three components of errors (chordwise, cascadewise, and angular displacement) on cascade performance are predicted. It is shown that cascade performance is more sensitive to blade setting errors in the stall region than in the design region. Setting errors of one blade of a cascade are shown to have a substantial effect on the pressure distribution of the two neighboring blades as well as an effect on the error blade itself. They increase the outlet total pressure loss and deteriorate the outlet angle distribution. It is noticed that flow around the error blade is more affected by the angular setting error near the blade midspan than near the cascade side walls. On the other hand, this phenomenon is seen to be reversed in the case of cascadewise error. The two regions are equally affected by chordwise setting error.

Nomenclature

AVR = axial velocity ratio ($\bar{C}_{x2}/\bar{C}_{x1}$)
C = fluid velocity
C_x = velocity component in the axial direction of cascade
c = blade chord length
C_p = local static pressure coefficient, $(P-P_1)/\frac{1}{2}\rho C_1^2$
h = blade span
i = inlet flow incidence angle
L = lift force
P = static pressure
P_0 = total pressure
Re = Reynolds number, $\rho c \bar{C}_1/\mu$
s = spacing
x = distance along chordline measured from leading edge
y = distance along cascade
z = distance along blade span
α = air angle measured from cascade normal
β = angle between chordline and cascade direction
μ = viscosity
ρ = fluid density
σ = stagger angle ($=90-\beta$)
Δ = incremental change in value

Subscripts

0 = for error-free cascade or stagnation value
1 = at cascade inlet
2 = at cascade outlet

Superscript

($-$) = pitch average value

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Introduction

ONE of the basic problems of turbomachines is the change in performance due to deviation of their blades from nominal conditions. Deviation of the turbomachine blades from nominal conditions falls into three main categories: change in the surface finish of the blades, change in the profile shape of the blade section, and inaccurate blade setting. The first two categories result primarily during machine operation. For example, in gas turbines these changes are caused by impurities in the working medium. The blades are attacked by erosion, corrosion, and contamination. As a result, the output and efficiency of the machine decrease. Experience shows that in many cases the blades of the first stages of gas turbines are thinned by erosion and corrosion and those of the last stages are thickened by deposits. Both of these phenomena are generally accompanied by roughening of the blade surface. The second category of deviation may also result from machining inaccuracy. The effect of surface roughness and profile changes on turbomachine performance was experimentally investigated by many authors (e.g., Refs. 1-6).

The third category (blade setting errors) is caused by machining inaccuracy as well as inadequate care during the assembly process. For example, in axial flow pumps, it was observed that impellers manufactured according to the same design had repeatedly nonidentical characteristics.[7] This variation was attributed to probable errors in blade setting due to inadequate care in assembly. Setting of turbomachine blades may also be distorted due to centrifugal and aerodynamic forces in the operation of the machine. Further, it is believed that setting errors are responsible, at least in part, for the discrepancy and scatter observed in experimental data reported by different investigators for cascade of identical geometry. Unfortunately, such possible errors do not usually appear in cascade data given in the literature. Gostelow,[8] who reports measured errors in the stagger angle of his cascade blades, is perhaps the only exception.

Blade setting errors may be classified as periodic or random. In practice, periodic distribution of setting errors relates to the class of axial turbomachines where the number of blades in each row is relatively small (e.g., axial flow fans and propeller pumps). The equivalent two-dimensional model for such a case is an infinite cascade with periodic setting errors in one or more blades. On the other hand, in axial machines having a large number of blades in each row (e.g., axial compressors and turbines), the error distribution, if any, may be considered nonperiodic, i.e., random.

A blade setting error may be resolved into three components: displacement parallel to the chordline (chordwise error), displacement parallel to the cascade direction (cascadewise error), and angular displacement about the midchord point (angular error). Any of these components may be positive or negative. The sign notation used in the present results is shown in Fig. 1.

The problem of periodic setting error was analyzed theoretically by El-Taher, et al.[9] The case of nonperiodic setting error was investigated theoretically[10] and experimentally.[11] However, the experimental investigations were restricted to the design range (i.e., the low incidence range). The main conclusions were: 1) the performance of the test cascade is more markedly affected by angular errors than it is by other types of error; 2) the presence of any of these errors results in substantial alteration in the pressure distribution of the error blade and one blade on each side; 3) further, the outlet flow angle is significantly affected by angular errors and hardly by other types; 4) no measurable effects on the outlet pressure have been indicated due to any of these errors.

The experimental work reported here illustrates the effect of one-blade nonperiodic setting errors on the stalling performance of the compressor cascade. This represents the basic case of nonperiodic error distribution. The cascade was tested over a range of values for the setting error components with a view to obtaining the individual effect of each component on cascade stalling performance. The effect of combining any two components of blade setting errors is dealt with by El-Taher.[12]

Experimental Setup

The solid wall blower tunnel sketched in Fig. 2 was used for the present investigation. The geometry of the test cascade when free of error was as follows:

Profile	10C4/30C50 (British convention)
Space/chord	0.85
Stagger angle	36 deg (measured from cascade normal)
Blade length	750 mm
Blade chord	180 mm
Number of blades	9

The general arrangement of the test cascade is shown in Fig. 3. Blade m was made adjustable so that any combination of setting error components could be imposed upon it, using the error selection mechanism shown schematically in Fig. 1. The other blades were permanently fastened to the side walls. All blades were cast from fiberglass using the same mold to insure that all profiles were identical. Traversing facilities were provided to the working section in order to carry out detailed measurements of the flow parameters at the inlet as well as at the outlet of the cascade. Measurements of outlet flow conditions were restricted in a plane one chord axially downstream from the trailing edge. In this plane the static pressure is atmospheric and it remains to measure total pressure and yaw angle. The pitot-yaw claw probe was found suitable for this purpose. Measurements of static pressure upstream of the cascade were made by means of seven static pressure holes on each side wall. These holes were located one chord ahead of the leading edge. Measurements of total pressure and yaw angle upstream of the cascade were also achieved by another pitot-yaw claw probe. The observed measurement errors were ± 1% for pressures and ± 0.2 deg for the flow angles.

Experiments

First, the cascade blades were assembled between the leading and trailing edge lines previously marked on the end walls. The stagger angle halfway between the end walls was then checked for all blades and the error was found to vary within 0.1 deg, which was adequate to consider the cascade to be error-free. A preliminary error-free test was run in which the Reynolds number was maintained in the region of 3.1×10^5 (based upon blade chord and upstream velocity). In this error-free test, which was carried out at an incidence

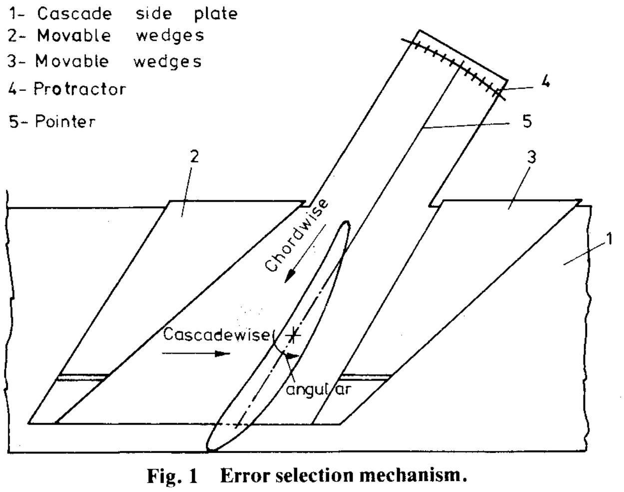

Fig. 1 Error selection mechanism.

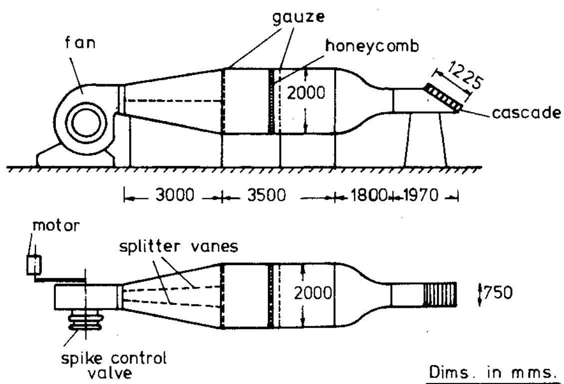

Fig. 2 General arrangement of cascade blower tunnel.

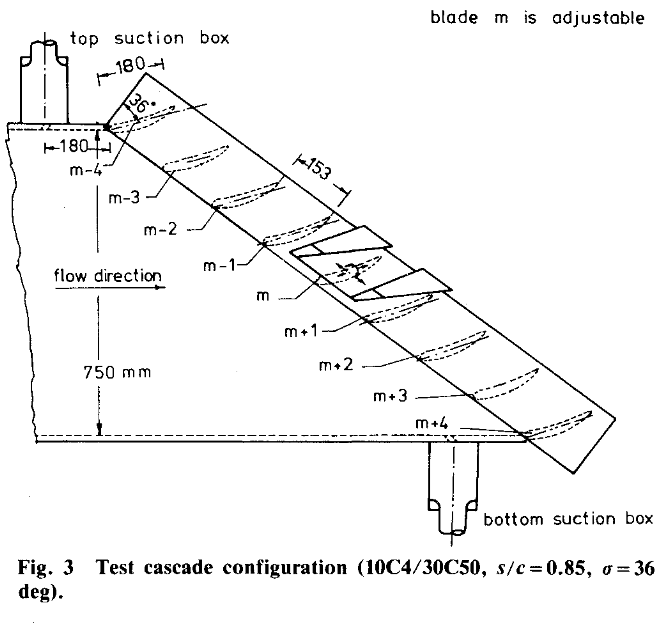

Fig. 3 Test cascade configuration (10C4/30C50, $s/c = 0.85$, $\sigma = 36$ deg).

angle of 9 deg, the axial velocity ratio was estimated at 1.33. These values of Reynolds number, incidence angle, and axial velocity ratio were maintained as closely as possible to the indicated values for all subsequent experiments. The central blade (designated m) was then set in error as predetermined for testing a range of one-error components at a time. Positive as well as negative values of errors were considered.

In each test, the midspan performance was first examined. Pressure distributions were recorded at midspan of the central three blades (blades m-1, m, and $m+1$). Surveys of total pressure and flow angle were made extending from the midspan location to the end wall and covering three blade pitches. The surveys were carried out one chord length downstream of the cascade. The individual effect of the varying error components on the aerodynamic performance is displayed in Figs. 4-15.

Results and Discussions

Chordwise Setting Error

Figure 4 shows the variation in lift of blades m and $(m+1)$ with a chordwise setting error. Results of the potential flow solution[10] and experimental results in the low incidence range[11] are also shown. The effects on the stalling range are evidently nonlinear. Both positive and negative chordwise setting errors decrease the lift of the blade in error. Also, the percentage change in lift of the error blade in the stalling range due to chordwise setting error is much less than the corresponding change in the design range. On the other hand, the change in lift for the blade facing the convex side of the error blade (blade $m+1$) is of the same order of magnitude as the error blade itself. However, the results in the design range[10,11] show that the change in the lift of the blade $(m+1)$ is one order of magnitude less than blade m. The results for the blade facing the concave side of the error blade, blade (m-1), were negligibly small and are therefore not shown.

Figure 5 shows the effect of positive as well as negative chordwise setting errors on wake traverses. The effect on the outlet angle is substantial and is localized in the central two blade pitches of the cascade. On the other hand, it is shown that this component of error has no effect on the outlet total pressure traverse. This can be better illustrated by Fig. 6 which shows that this component of setting error has no effect on the pitch averaged values of total pressure, even near the side walls of the cascade. This means that chordwise setting error has no effect upon either the cascade blades, boundary layers or the stalling area on the side walls. This can be further explained by use of Fig. 7 which shows that the effect of $\Delta x/c = -0.1$ on the pressure distribution of the cascade blades is small. Therefore, boundary layers on the blades and on the side walls are not affected by this component of error.

Cascadewise Setting Error

Figure 8 shows the effect of cascadewise setting error on the lift of various blades. The figure also shows results of the potential flow solution[10] and experimental results in the low incidence range.[11] It appears that while the effect is linear in the design range, it is nonlinear in the stall range. Also, while the change of lift of the two adjacent blades is of opposite sign

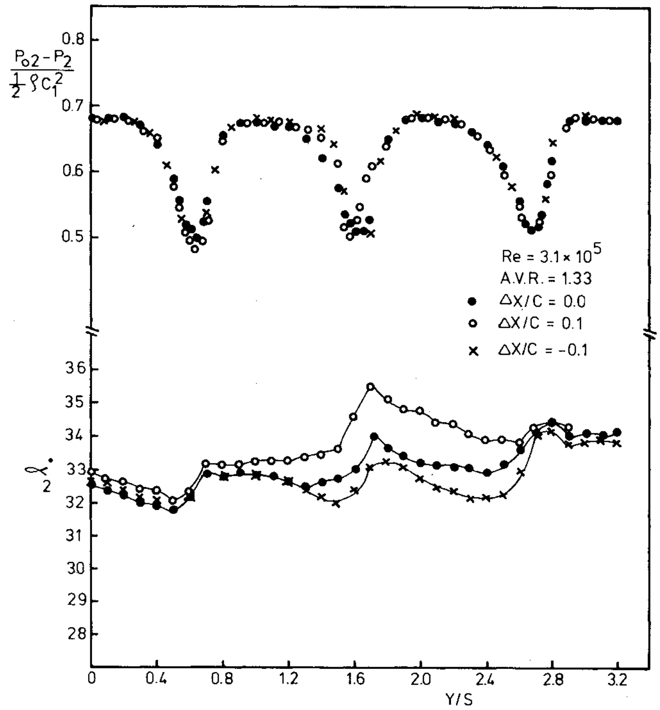

Fig. 5 Wake traverses with one-blade chordwise setting errors (one chord length downstream).

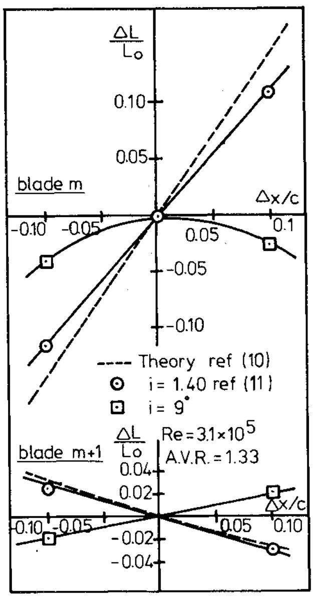

Fig. 4 Change in lift vs chordwise setting error.

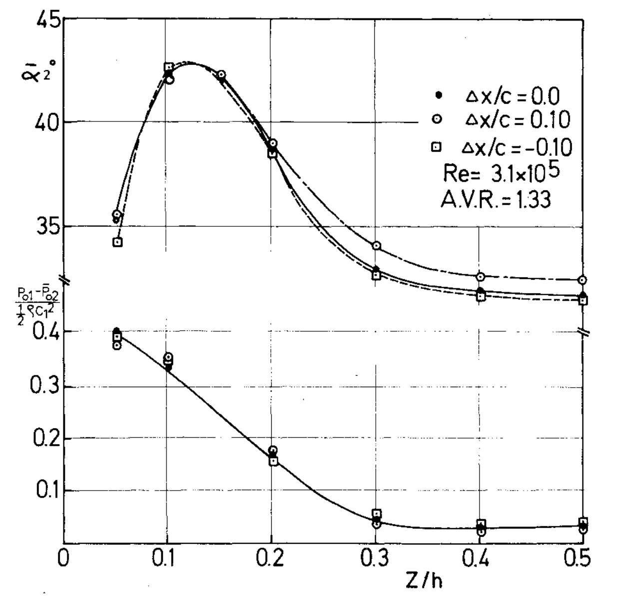

Fig. 6 Integrated outlet angle and total pressure loss vs spanwise position with one-blade chordwise setting errors.

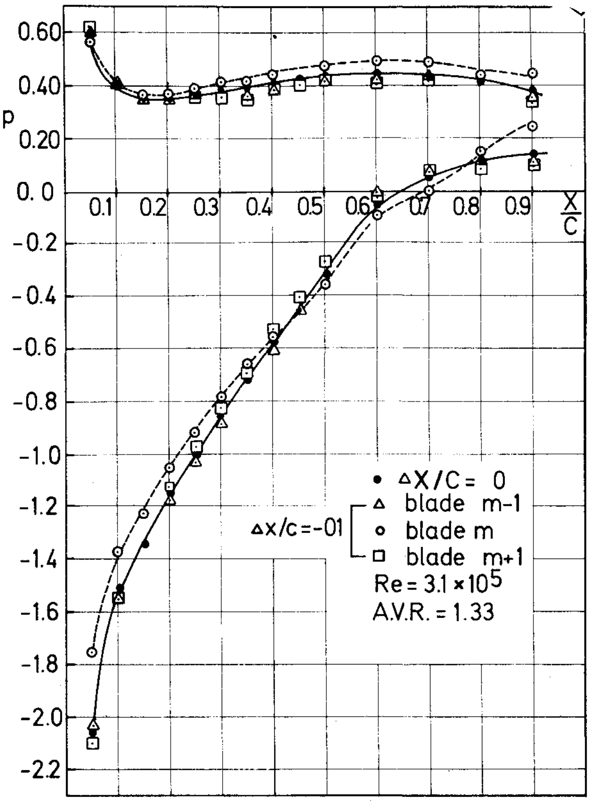

Fig. 7 Pressure distribution of various blades in presence of one-blade chordwise setting error.

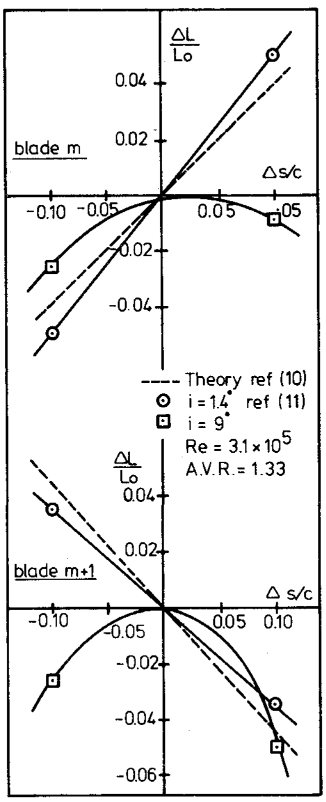

Fig. 8 Change in lift vs cascadewise setting error.

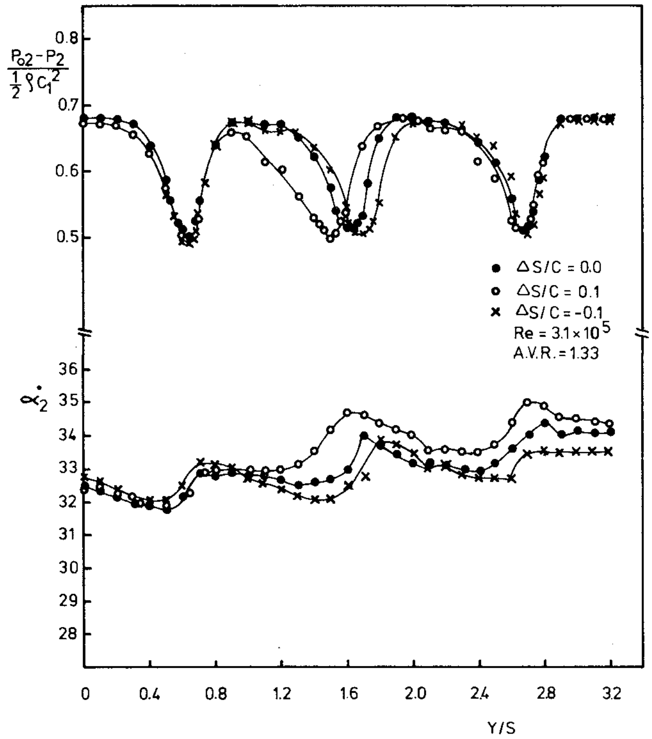

Fig. 9 Wake traverses with one-blade cascadewise setting errors (one chord length downstream).

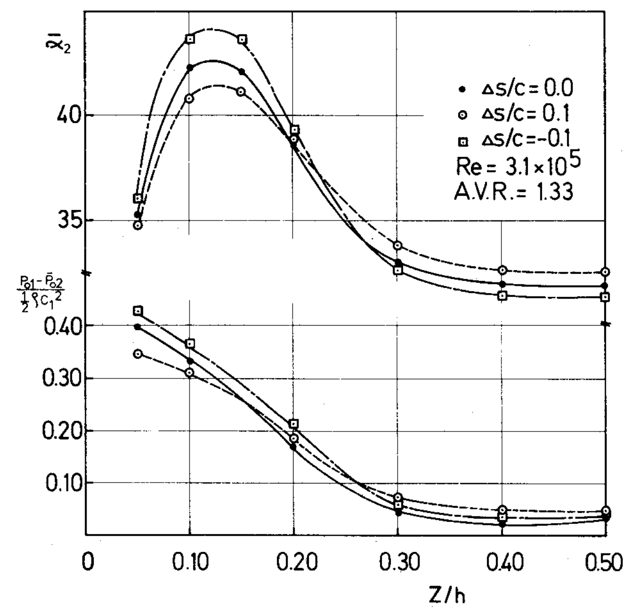

Fig. 10 Integrated outlet angle and total pressure loss vs spanwise position with one-blade cascadewise setting errors.

in the low incidence range, it is of the same sign in the high incidence range. Since the sum of changes in the loading of cascade blades is small in the design range, it is shown that the effect on the outlet angle is negligible.[11] However, in the stall range the sum of changes in the loading of different blades is appreciable and therefore cascadewise setting error has a considerable effect upon the outlet flow angle. This can be shown by Fig. 9. It appears also from this figure that positive as well as negative cascadewise errors increase the outlet total pressure loss. This can be compared with Fig. 5 which shows that the chordwise setting error has no effect on the total pressure traverse.

Figure 10 shows the effect of cascadewise setting error upon the pitch averaged values of outlet angle and outlet total pressure. It appears that the effect is larger near the cascade side walls than in the central part of the cascade. This can be

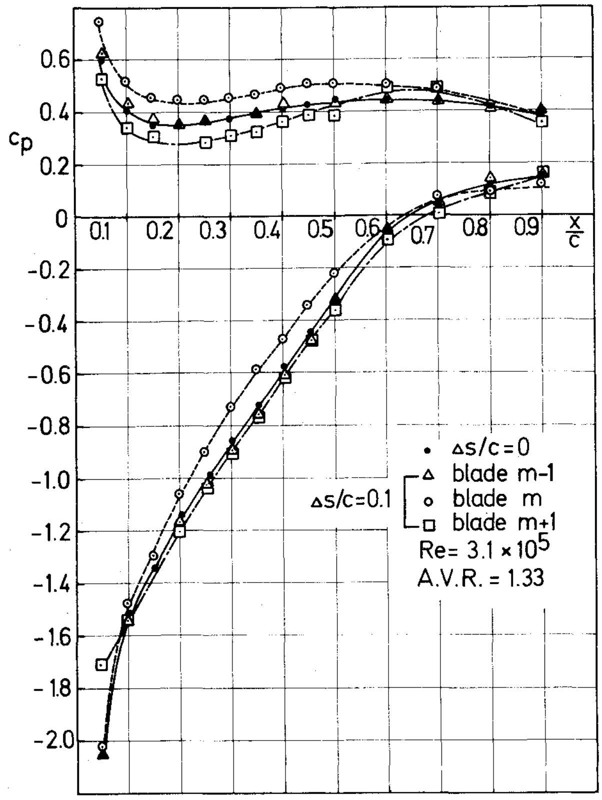

Fig. 11 Pressure distribution of various blades in presence of one-blade cascadewise setting error.

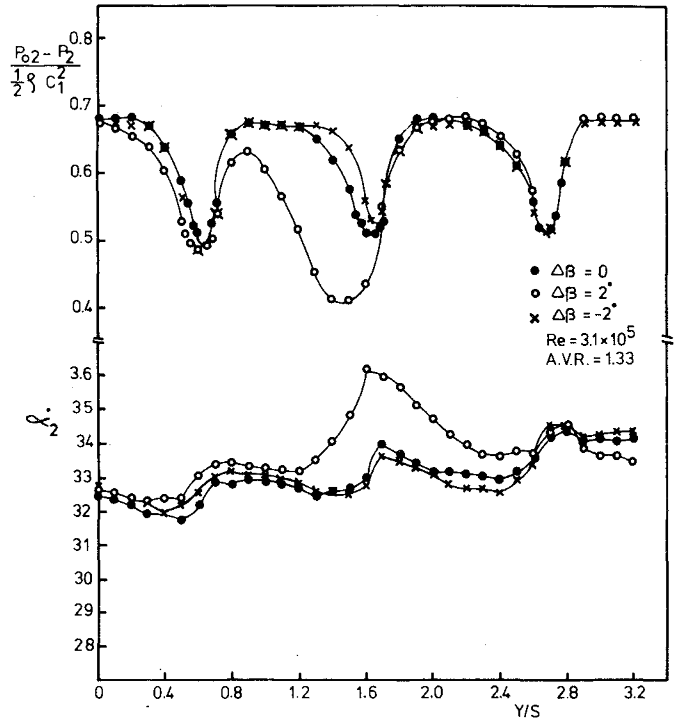

Fig. 13 Wake traverses with one-blade angular setting errors (one chord length downstream).

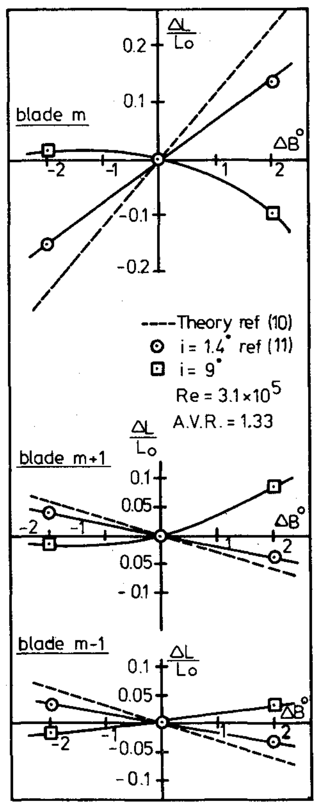

Fig. 12 Change in lift vs angular setting error.

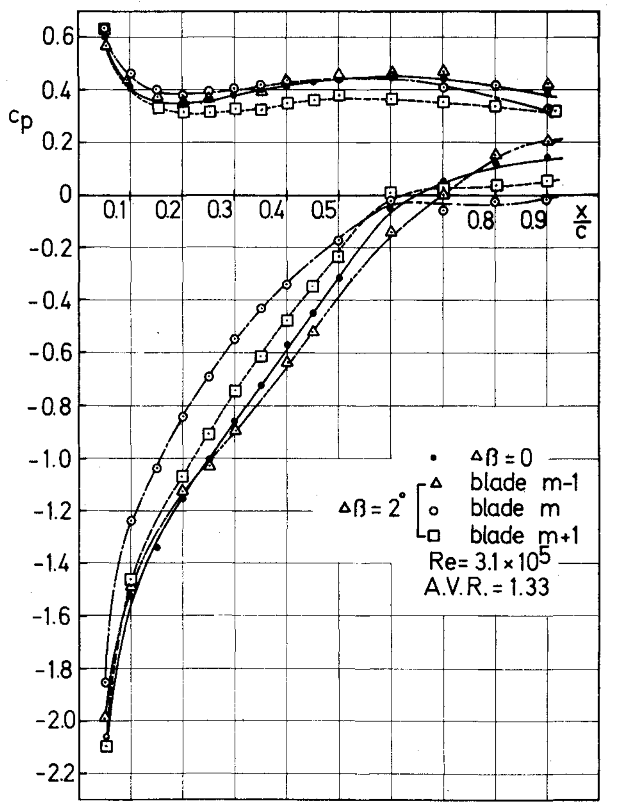

Fig. 14 Pressure distribution of various blades in presence of one-blade angular setting error.

explained by the fact that the mean velocity decreases near the side walls, which means a lower value of Reynolds number near the side walls. Therefore, the change in the pressure distribution due to setting error causes an earlier separation of boundary layers on the suction side of the blades near the side walls. Also the separation area on the cascade side walls increases due to the change in the pressure field of the error blade.

Figure 11 shows the effect of cascadewise error on the pressure distribution of various blades. If it is compared with Fig. 7 it indicates that while the pressure distribution of blade $(m+1)$ is slightly affected by chordwise setting error, it is

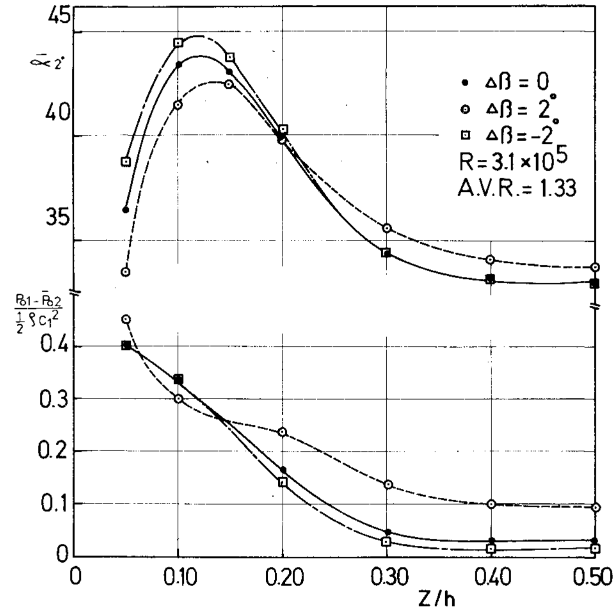

Fig. 15 Integrated outlet angle and total pressure loss vs spanwise position with one-blade angular setting errors.

appreciably affected by cascadewise setting error. It appears also that the effect of cascadewise error on the pressure distribution of the error blade (m) and the first blade to the convex side ($m+1$) is of the same order of magnitude.

Angular Setting Error

Figure 12 shows the effect of angular error in the setting of blade m on the lift of the various blades. As in the case of chordwise and cascadewise setting errors, the effects of angular errors are also nonlinear. The percentage change in the lift of the different blades are of the same order of magnitude as that in the low incidence range. However, the change in lift in the stalling range is opposite in sign to the change in the near design range.

Figure 13 shows the midspan wake traverses one chord downstream of the cascade. The figure shows the drastic increase in the outlet total pressure loss in the case of positive angular setting error. This increase in pressure loss is due to flow separation on the blade suction surface. This flow separation is indicated in Fig. 14 in the form of the flat part of the pressure distribution in the rear half of blade m. Figure 14 also shows that separation takes place on the suction surface of blade ($m+1$).

Figure 15 shows that while positive angular setting error causes an increase in the pitch averaged value of the outlet angle in the central part of the cascade, it causes a decrease in the outlet angle near the cascade side walls. Likewise, the negative angular setting error causes no change in the outlet angle in the central part of the cascade, but its effect is appreciable near the side walls. Figure 15 also shows that the increase in the total pressure loss in the central part of the cascade due to positive angular setting error is much larger than the increase in the total pressure loss near the side walls. This can be explained as follows: In the case of a cascade with no setting errors, the blades have not stalled in the central part of the cascade, but they are stalled near the side walls.[13] Therefore, angular setting error causes blade stall in the central part of the cascade and a large increase in total pressure loss. This angular setting error has little effect on the wake near the side walls because the blade has already stalled at this location.

Conclusions

1) Setting errors have substantial effects upon the stalling performance of cascades. Such errors must therefore be reported in conjunction with cascade data to validate comparison of results by different investigators.

2) In the stalling range, setting errors effects are nonlinear.

3) Blade setting errors have a substantial effect upon the pressure distribution of various blades. They increase the outlet total pressure loss and deteriorate the outlet flow angle distribution.

4) The increase in the outlet flow angle in the central part of the cascade (due to setting errors) is accompanied by a decrease in the outlet angle near the cascade side walls.

5) The effects of the various components of blade setting error are quite different in nature, i.e.,

a) Chordwise setting error has little effect upon the pressure distribution of various blades. It has no effect upon the outlet total pressure. The change in the outlet angle near the axis of the cascade due to chordwise setting error is of the same order of magnitude as in the region near the side walls.

b) Cascadewise setting error has a large effect upon the pressure distribution of various blades. It increases the outlet total pressure loss and causes a pronounced change in the outlet flow angle. Its effect is larger in the region near the side walls than in the central part of the cascade.

c) Positive angular setting error causes stall of the various blades, accompanied with a large increase in the outlet total pressure loss and a large variation in the outlet flow angle. On the other hand, angular setting errors effects are larger near the axis of the cascade than in the region near the side walls of the cascade.

References

[1] Turner, R. C. and Hughes, H. P., "Tests on Rough Surface Compressor Blading," Current Paper 206, Aeronautical Research Council, 1956.

[2] Ida, T., "The Effect of Impeller-Vane Roughness and Thickness on Characteristics of the Mixed-Flow Pump," *JSME Bulletin*, Vol. 8, Nov. 1965, pp. 634-643.

[3] Bammert, K. and Stobbe, H., "Measurements on Multistage Axial Turbine with Normal, Thinned, and Thickened Blade Profiles," *Motorechnische Zeitschrift*, Vol. 31, No. 5, 1970, pp. 189-198.

[4] Bammert, K. and Stobbe, H., "The Effect of Corrosion, Erosion and Contamination on the Operation Behaviour of Turbine and Circuit of Gas Turbine Plant," *Archiv F. Eisenhuttenwess*, Vol. 41, No. 11, 1970, pp. 1055-1068.

[5] Bammert, K. and Sandstede, H., "Measurements Concerning the Influence of Surface Roughness and Profile Changes on the Performance of Gas Turbines," *Journal of Engineering for Power, Transactions of ASME*, Series A 94, July 1972, pp. 207-213.

[6] Baibakov, O. V., "The Effect of Surface Roughness in a Centrifugal Pump," *Russian Engineering Journal*, Vol. 46, No. 10, 1966, pp. 27-31.

[7] Rashed, M. I., unpublished work on the performance of propeller pumps, Cairo University, 1973.

[8] Gostelow, J. P., "The Accurate Prediction of Cascade Performance," Ph.D. Thesis, Liverpool University, 1965.

[9] El-Taher, R. M., Shaalan, M. R., and Rashed, M. I., "The Effect of Periodic Errors in Blade Setting on the Potential Incompressible Flow in Compressor Cascades," *Journal of Fluids Engineering, ASME Transactions*, March 1978.

[10] El-Taher, R. M., Shaalan, M. R., and Rashed, M. I. "The Effect of Random Errors in Blades Setting on the Potential Incompressible Flow in Compressor Cascade," *Journal of Fluids Engineering, ASME Transactions*, Dec. 1976.

[11] El-Taher, R. M., Shaalan, M. R., and Rashed, M. I., "An Experimental Investigation into the Effect of Errors in Blade Setting on the Low-Speed Performance of a Compressor Cascade," *Journal of Engineering Science*, Vol. 3, No. 2, 1977, College of Engineering, University of Riyadh.

[12] El-Taher, R. M., "The Effect of Combined Errors in Blade Setting on the Stalling Performance of a Compressor Cascade," *Bulletin of the Faculty of Engineering*, Cairo University, 1977-1978 (Aeronautical Engineering Paper 6).

[13] Shaalan, M. R., "A Wind-Tunnel Investigation of the Stalling Performance of Two Compressor Cascades of Different Aspect Ratios at Low-Speed," Aeronautical Research Council, C.P. 1103, 1970.