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Effect of Positive Preswirl Angle and Velocity on Centrifugal Compressors Performance

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تأثير زاوية التدويم المسبق الموجب وسرعته على أداء الضواغط الطاردة

أظهرت الدراسة الحالية تأثيرا كبيرا للدوامات القسرية المسبقة الموجبة وزاوية التدويم وسرعته على أداء الضواغط الطاردة لحالات التشغيل على سطح الأرض وفي حالة الطيران. بالنسبة إلى زاوية التدويم المسبق وسرعته، فإنه يساوي ٦٠ درجة و ١٥٠ م/ث، نقص الشغل الفعلي النوعي اللابعدي إلى ٨١,٤٪ و٨٩٪ على التوالي بالنسبة للطريقة الدقيقة وبالنسبة للطريقة التقريبية إلى ٧٢,٨٪ و٨٣,٥٪. كذلك، نقصت نسبة ضغط الركود الإجمالي إلى ٧٩,٧٪ و٨٧,٦٪ على التوالي بالنسبة للطريقة الدقيقة وللطريقة التقريبية إلى ٧١,٤٪ و٨٢,٢٪. كذلك، نقص الماخ النسبي عند أعلى مدخل الدافعة بـ ٥٤,٣٣٪ و٥٠,١٥٪ على التوالي عند حالات التشغيل على سطح الأرض على حساب خسارة في نسبة الضغط مقداره ٢٠,٣٪ و١٢,٤٪ على التوالي. زيادة على ذلك، كانت قيم الماخ عند ارتفاع ١١٠٠٠م هي ٠,٤٨٠٩ و ٠,٥١٨٧على التوالي بدلا عن ١,٠٥٣ من دون تدويم مسبق والذي يحدث تأثيرا كبيرا على اتزان الضاغطة وأدائها. تخلص النقص في الماخ تماما من تأثير الإنضغاطية وألغى تكوين الصدمات. بناء عليه، تحققت حالات تشغيل آمنة جدا وأكثر اتزاناً لمحركات الطائرات حتى عند ارتفاعات الطيران. والنتيجة هي إحداث نقص في تدهور الأداء بسبب إلغاء تكوين الصدمات والخسائر المترتبة عليه إلى جانب نقص كبير في التلوث الضجيجي.

Abstract

The present study showed a significant effect of forced-vortex positive preswirl angle and velocity on centrifugal compressors performance for ground and flight operating conditions. For the used preswirl angle and velocity of 60º and 150 m/s, the exact method decreased the normalized actual specific work to 81.4% and 89%, respectively, while for the approximate one it decreased it to 72.8% and 83.5%. In addition, the exact method reduced the pressure ratio to 79.7% and 87.6%, respectively while for the approximate one decreased it to 71.4% and 82.2%. Also, the relative Mach number at impeller eye tip was decreased to 54.33% and 50.15%, respectively at ground operating conditions at the expense of 20.3% and 12.4% sacrifice in pressure ratio, respectively. Moreover, the Mach values at 11000m altitude become 0.4809 and 0.5187, respectively instead of 1.053 without preswirl, which causes a significant impact on compressor stability and performance. The decreased Mach number completely eliminates the compressibility effect and avoids the formation of shocks. Thus, the operating conditions of aircraft engines become very safe and more stable even at flight altitudes. The result is a reduction in performance deterioration due to elimination of shocks and consequent losses besides a much less noise pollution.

Keywords: Forced-vortex, positive preswirl angle and velocity, centrifugal compressors performance.

INTRODUCTION

The rotating impeller of a centrifugal compressor imparts energy to the continuously flowing gas. When this impeller rotates, the gas is drawn in through the eye. The absolute velocity of the inflow gas into the eye is axial. The gas then flows radially through the impeller passages due to centrifugal forces. Most of the input mechanical power driving the compressor is transmitted into the gas in the impeller **(**Khajuria & Dubey 1988**).** The rotating impeller imparts the gas a high kinetic energy and a small pressure rise during its radial flow. Compression is less affected by boundary layer growth and separation due to adverse pressure gradient (Kerrebrock 1992).

The chief advantages of centrifugal compressors over axial flow ones are: higher stage pressure ratio, simplicity besides ruggedness of construction, convenience for installation with intercoolers and/or heat exchangers, smaller in length, do not deteriorate performance due to contaminated gas, perform efficiently over a wide range of mass flow, no loss of performance due to build up of deposits on surfaces of gas passages and wider range of stable operation between surging and choking limits at a particular rotational speed. Centrifugal compressors are preferred over the axial ones because simplicity, light weight, ruggedness and less cost (Wilson & Korakianitis 1999) are more important than maximum efficiency and small diameter especially in aircraft engines. Centrifugal compressors were superseded by axial flow ones in jet aircraft engines. However, their use is a must for short overall engines and when deposits are to be formed on surfaces of gas passages **(**Ganesan 2006; Bathie 1996).

Compressors designed for maximum efficiency operate well with a single restriction in operating conditions. The maximum efficiency of centrifugal compressors for a pressure ratio in the range of 3 to 9 occurs over a positive preswirl angle in the range of 25 to 40º (Meherwan 2002). However, compressors must have reasonable efficiency over a wide range of operating conditions **(**Harman 1981**)**. Centrifugal compressors are widely used in industry and small power units. This is mainly because higher efficiency of axial flow compressors cannot be maintained for small size ones. Most current proposals for vehicular gas turbines utilize centrifugal compressors in heat exchange cycles.

Without inlet guide vanes, the gas flow enters the impeller axially and the impeller blades must be curved in the direction of rotation for smooth entry. This curvature varies, at the eye, from root to tip depending on the axial velocity and impeller rotational speed (Bathie 1996). There is a possibility for the flow to separate from the convex face of the eye forming shocks with consequent losses (Najjar & Aqeel 2002) if the relative velocity at impeller eye tip becomes closer to or greater than the sonic speed. Such shocks choke the impeller eye and affect the compressor performance (Rodgers & Shapiro 1973; Balje 1981).

The gas flow is deflected, using inlet fixed guide vanes ahead of the impeller eye, to enter with a preswirl angle instead of entering purely axial (Khajuria & Dubey 1988; Mathur & Sharma 1988). Parabolic variation of the preswirl angle from zero at impeller root to 40º at the tip using twisted inlet guide vanes decreased the relative Mach number at impeller eye tip by about 32% and restored the work done as well as the pressure ratio (Najjar & Aqeel 2002). Besides reducing such Mach, the curvature of the impeller vanes at the inlet decreases as the preswirl angle increases (Khajuria & Dubey 1988).

Recently, the trend is to use a centrifugal stage together with one or more axial stages for small turbofan and turboprop aircraft engines. Centrifugal compressors and fans are devices used to increase the gas pressure, but they differ in their task. A fan increases the gas pressure slightly and it is mainly used to move gas around. A compressor compresses gas into a prescribed high pressure. Centrifugal compressors are turbomachines that employ centrifugal effects to increase the gas pressure.

The objective of the present study is to create a forced-vortex positive preswirl angle and velocity using fixed inlet guide vanes ahead of the impeller eye in order to reduce the inlet relative Mach number. The aim is to keep the flow attached at the eye convex face in order to completely prevent formation of shocks and consequent losses. The goal is to reduce performance deterioration, decrease noise pollution and achieve safe besides more stable operating conditions of aircraft engines.

INLET GUIDE VANES

In centrifugal compressors, the gas enters the eye axially and is turned through a specific angle into the impeller using fixed inlet guide vanes, FIGVs installed ahead of the impeller eye. The magnitude and direction of the entering relative velocity along the eye depends on the impeller peripheral speed, the magnitude and direction of the absolute velocity there. The relative velocity increases along the eye from root to tip hence, the relative Mach number at impeller eye tip, M_{1t}, has the highest value. Seven sets of FIGVs were used to create seven different constant preswirl angles from 0 to 60º with a step of 10º. When one set was installed, it created a forced-vortex positive constant preswirl angle over the impeller eye from root to tip in the direction of impeller rotation. Another seven sets of FIGVs were used to produce seven different constant preswirl velocities from 0 to 150 m/s with a step of 25 m/s. When one set was installed it creates a forced-vortex positive constant preswirl velocity, V_{u1}, over the impeller eye from root to tip in the direction of impeller rotation. Thus, it is possible to use smooth bent FIGVs that introduce preswirl into the impeller eye in order to reduce M_{1t} and avoid formation of shocks.

In the present study, the inlet section of the impeller is provided with installed set of FIGVs to produce a specified preswirl along the eye. The FIGVs deflects the gas flow tangentially with circumferential velocity at a fixed rate depending on the created preswirl at the eye. Such FIGVs may be located radially at inlet duct when axial entry is not available. Figure 1 shows the inlet velocity diagrams with and without positive preswirl (Meherwan 2002). In this figure, U_1, V_1, V_{a1}, W_1, V_{u1} and α are the peripheral speed, absolute velocity, axial velocity, relative velocity, positive preswirl velocity and angle, respectively at the impeller eye local radius, r_1. The change of operating parameters affects velocity triangles, which influences the energy transfer (Yahya 1983). The introduced forced-vortex preswirl also changes the energy transfer, hence, affects the work done and related performance parameters.

THEORETICAL ANALYSIS

When V_{u1} is constant along the eye, the specific angular momentum increases from root to tip. Thus, the specific work done depends upon the gas entering radius into the eye. A mean value of such work may be computed, based on impeller eye mean radius, $r_{1m} = (r_{1t} + r_{1r})/2$, where r_{1r} and r_{1t} are the impeller eye root and tip radii, respectively. The theoretical specific torque, τ, based on r_{1m} is given by

$$\tau = V_{u2} r_2 - V_{u1m} r_{1m} \tag{1}$$

where, $V_{u1m} = V_{a1m}*\tan(\alpha)$, r_2, V_{u2} and V_{a1m} are the preswirl velocity at r_{1m}, impeller exit radius, swirl velocity at r_2 and axial velocity at r_{1m}, respectively. The subscripts 1m and 2 refer to the stations at impeller eye mean radius and impeller exit, respectively. Introducing the slip factor, $\sigma = V_{u2}/U_2$, τ is expressed as

$$\tau = s\ U_2 r_2 - V_{u1m} r_{1m} \tag{2}$$

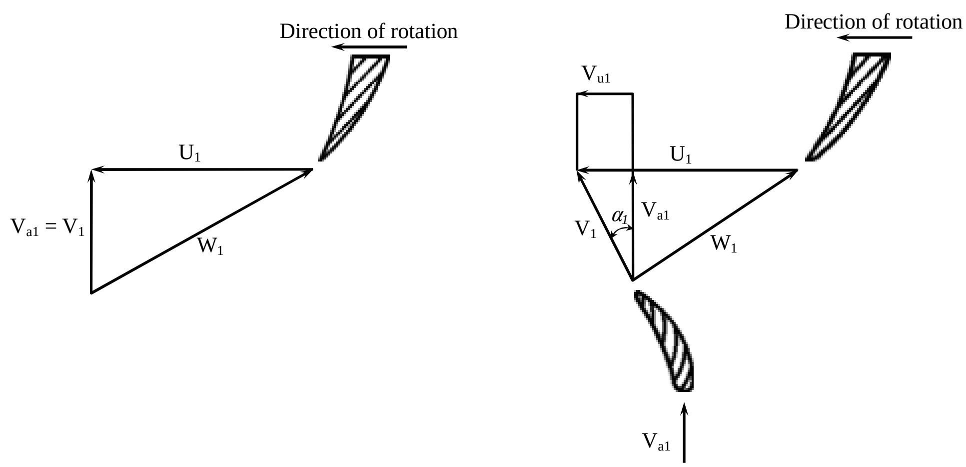
where, U_2 is the impeller peripheral speed at r_2. The τ, based on variable V_{u1} is given by

$$\tau = s\ U_2 r_2 - (V_{u1} r_1) \tag{3}$$

The theoretical specific work, w, is expressed as

$$w = \omega\tau \tag{4}$$

where, ω is the angular velocity.



(a) without preswirl (b) with positive preswirl

Fig. 1: Inlet velocity diagrams with and without preswirl.

PRACTICAL CONSIDERATIONS

Introducing the power input factor, ψ, to account for the friction and other losses, the actual specific work, w_A, is given by:

$$w_A = \psi w \tag{5}$$

The overall stagnation temperature rise, ΔT_0, becomes:

$$\Delta T_0 = \frac{w_A}{C_p} \tag{6}$$

where, C_p is the mean specific heat at constant pressure. The overall stagnation pressure ratio, $R = P_{03}/P_{01}$, is:

$$R = \left(1 + \frac{\eta_c \Delta T_0}{T_{01}}\right)^{\frac{\gamma}{(\gamma-1)}} \tag{7}$$

where, P_{01}, P_{03}, T_{01}, η_c and γ are the stagnation pressures at impeller eye as well as diffuser casing exit, stagnation temperature at impeller eye, compressor isentropic efficiency and specific heats ratio, respectively. Finally, M_{1t} is given by:

$$M_{1t} = \frac{W_{1t}}{\sqrt{\gamma R_0 T_{1t}}} \tag{8}$$

where, W_{1t}, T_{1t} and R_0 are the relative velocity and static temperature at r_{1t} as well as the ideal gas constant, respectively. The $(V_{u1}r_1)$ in Eq. (3) is computed from:

$$(V_{u1}r_1) = \int_{r_{1r}}^{r_{1t}} V_{u1}\, dr_1 \tag{9}$$

W_{1t} and T_{1t} in Eq. (8) are given by:

$$W_{1t} = \sqrt{(U_{1t} - V_{u1t})^2 + V_{a1t}^2} \tag{10}$$

and

$$T_{1t} = T_{01} - \frac{V_{a1t}^2 + V_{u1t}^2}{2C_p} \tag{11}$$

where, U_{1t}, V_{a1t} and V_{u1t} are the peripheral speed, axial velocity and preswirl velocity, respectively with all at r_{1t}.

The performance parameters are calculated for two forced-vortex preswirl flows, the constant α and the constant V_{u1} as follows:.

1. Constant α

The primary form of preswirl, in literature, is based on free-vortex flows. This requires $V_{a1} = V_{a1m}$ = constant along the impeller eye from root to tip (Najjar & Aqeel 2002). Conditions other than constant V_{a1} may be used for forced-vortex flows in which the radial equilibrium requirement should be satisfied. It is desirable to use a constant α in order to avoid manufacturing vanes of varying curvature along the impeller eye. The governing local equation of such flow, based on constant α is (Cohen et al. 2001; Balje 1981; Dixon 2006).

$$V_{u1} = V_{u1m}\left(\frac{r_{1m}}{r_1}\right)^{\sin^2\alpha} \tag{12}$$

Substituting Eq. (12) into Eq. (9) and upon integration, gives

$$\left(V_{u1}r_1\right) = \frac{r_{1r}\,V_{u1m}}{\left(1-\sin^2\alpha\right)}\left(\frac{r_{1m}}{r_{1r}}\right)^{\sin^2\alpha}\left\{\left(\frac{r_{1t}}{r_{1r}}\right)^{(1-\sin^2\alpha)} - 1\right\} \tag{13}$$

For constant positive preswirl angle, α, the performance parameters were calculated for two cases, the exact method along the impeller eye and the r_{1m} basis method.

2. Constant V_{u1}

The other forced-vortex preswirl flow is based on constant preswirl velocity, $V_{u1} = V_{u1m}$ = constant, where the distribution of the axial component is described by (Balje 1981; Möehle 1961).

$$V_{a1}^2 = V_{a1m}^2 + 2\,V_{u1m}^2 \ln\left(\frac{r_{1m}}{r_1}\right) \tag{14}$$

For this case, Eq. (9) gives

$$\left(V_{u1}r_1\right) = V_{u1m}\,r_{1r}\left\{\left(\frac{r_{1t}}{r_{1r}}\right) - 1\right\} \tag{15}$$

For constant positive preswirl velocity, V_{u1}, the performance parameters were also computed for two cases, the exact method along the impeller eye and the r_{1m} basis method.

COMPUTATIONAL PROCEDURE

All the performance parameters were computed for different constant values of positive preswirl angle, α, over the impeller eye from root to tip starting from 0 to 60º with a step of 10º. The computed parameters were repeated for constant different values of V_{u1} positive preswirl over the impeller eye from root to tip starting from 0 to 150 m/s with a step of 25 m/s. The choice of α range from 0 to 60º is because the maximum efficiency of centrifugal compressors for the present pressure ratio occurs at α of about 30º (Meherwan 2002). The choice of V_{u1} higher value of 150 m/s is because its limiting value at which V_{a1} becomes zero, is about 189 m/s at r_{1t} from Eq. (14).

The M_{1t} is dependent on the computational methods, r_{1m} basis or exact, and depends only on the created preswirl at the eye tip. The M_{1t} was computed from Eq. (8) employing Eqs. (10) and (11). Using r_{1t} instead of r_1, V_{u1t} needed to calculate M_{1t} was obtained from Eqs. (12) and $V_{a1t} = V_{a1tm}$ is constant for the constant α case. Using r_{1t} instead of r_1, V_{a1t} was obtained from Eq. (14) for constant V_{u1} and $V_{u1t} = V_{u1m}$. The approximate method, r_{1m} basis, calculations started using Eq. (2) to compute τ for constant α alone over the impeller eye from root to tip. w, w_A, ΔT_0 and R were then computed, based on r_{1m} from Eqs. (4) to (7). In the exact method of closed form integration, these parameters were computed along the impeller eye from Eqs. (3) to (7), using Eq. (13) for the constant α and Eq. (15) for the constant V_{u1} cases.

The main performance parameters (τ, w, w_A and ΔT_0) were normalized using the corresponding ones for $\alpha = 0$, while R and the most important parameter, $M_{1t,}$ are already dimensionless. Thus, the results become applicable for different geometries and operating conditions. The normalized specific torque, theoretical specific work and overall stagnation temperature rise coincide on the normalized actual specific work, $w_{An} = w_A/w_{A0}$. Thus, only w_{An}, R and M_{1t} are presented in this study. The w_{A0} is such parameter of the exact method for $\alpha = 0$.

The particulars of design and operating variables required for the present study calculations were chosen for a typical centrifugal compressor of a small aircraft engine (Cohen et al. 2001; Logan 1993;Mattingly 1996). They are the impeller radius at exit r_2 = 0.25 m, r_{1t} = 0.15 m, r_{1r} = 0.075 m, impeller rotational speed N = 290 rps, V_{a1m} = 143 m/s, σ = 0.9, ψ = 1.04, η_c = 0.78 and T_{01} = 295 K.

RESULTS AND DISCUSSION

Figure 2 depicts the variation of w_{An} with α using the exact method and the approximate one. Without preswirl angle, $\alpha = 0^o$, w_{An} has the same value for both cases. It is clear that w_{An} shows a quadratic decrease with α for both cases. The rate of decrease of w_{An} with α for the exact method is lower than that of the approximate one. For $\alpha = 60^o$, w_{An} of the exact method has the higher value with a lower decrease of 18.6% of its value at $\alpha = 0^o$. In addition, w_{An} of the approximate method has the lower value with the higher decrease of 27.2%. Also, the exact method computation reduced w_{An} to 81.4% and the approximate method calculation reduced w_{An} to 72.8%. Moreover, the difference in w_{An} is 8.6% in favor of the exact method.

Figure 3 reflects the change of w_{An} with V_{u1} using both the exact and the approximate methods. Without preswirl velocity, $V_{u1} = 0$, w_{An} has the same value for both cases. It is clear that w_{An} shows an almost linear decrease with α for both cases. The rate of decrease of w_{An} with V_{u1} for the exact method is lower than that of the approximate one. For V_{u1} = 150 m/s, w_{An} of the exact method has the higher value with a lower decrease of 11% of its value at $V_{u1} = 0$. In addition, w_{An} of the approximate method has the lower value with a higher decrease of 16.5%. Besides that, the exact method computation decreased w_{An} to 89% and the approximate method calculation reduced w_{An} to 83.5%. Therefore, the difference in w_{An} is 5.5% in favor of the exact method. Comparing the α and V_{u1} cases using the exact method, the difference in w_{An} is 7.6% in favor of V_{u1} case.

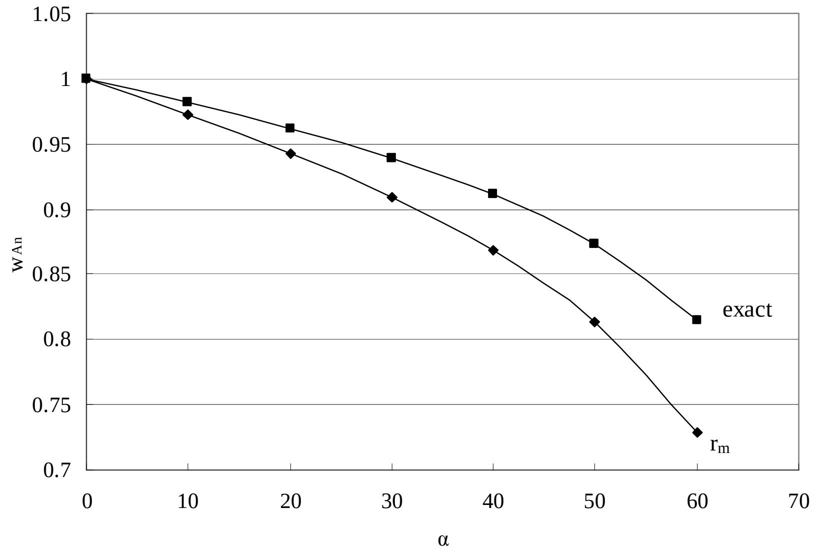


Fig. 2 Variation of w_{An} with α for r_{1m} basis and exact methods.

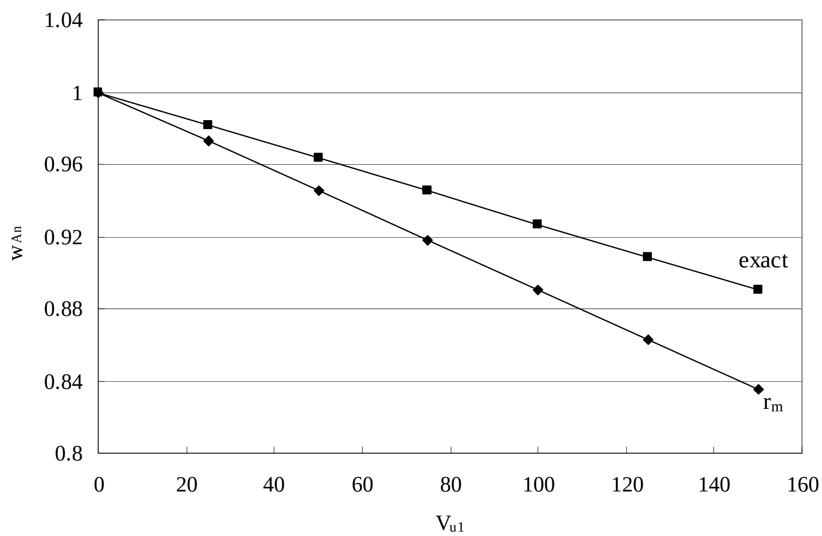


Fig. 3: Variation of w_{An} with V_{u1} for r_{1m} basis and exact methods.

Figure 4 shows the change of R with α using the exact method and the approximate one. Without preswirl angle, α = 0º, R has the same value for both cases. It is clear that R reflects a quadratic decrease with α. The rate of decrease in R with α of the r_{1m} basis method is higher than that of the exact method. For α = 60º, R of the approximate case has the lower value with a higher decrease of 28.7% of its value with α = 0º. In addition, R of the exact method has the higher value with a lower decrease of 20.3%. Furthermore, the exact method computation reduced R to 79.7% and the approximate method calculation decreased R to 71.4%. Moreover, the difference in R is 8.4% in favor of the exact method.

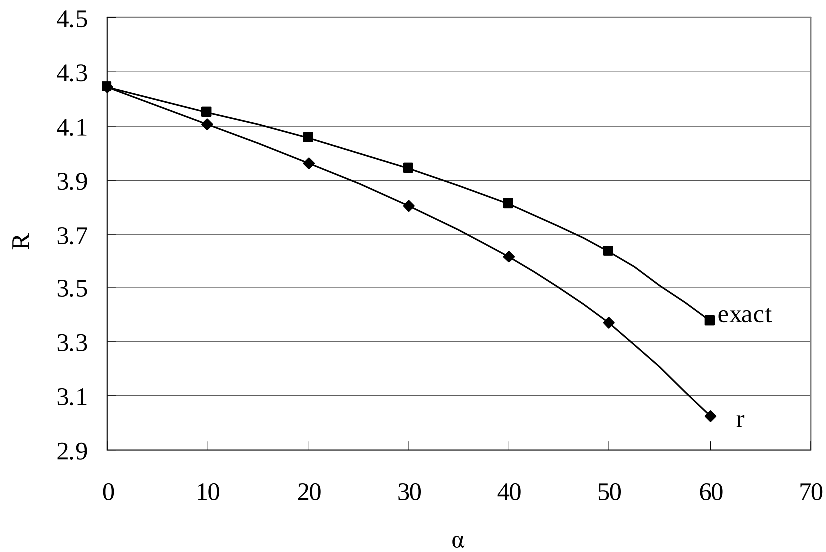


Fig. 4: Variation of R with α for r_{1m} basis and exact methods.

Figure 5 indicates the change of R with V_{u1} using both the exact and the approximate method. Without preswirl velocity, $V_{u1} = 0$, R has the same value for both cases. It is clear that R reflects an almost linear decrease with V_{u1}. The rate of decrease in R with V_{u1} of r_{1m} basis method is higher than that of the exact method. For V_{u1} = 150 m/s, R of the exact method has the higher value with a lower decrease of 12.4% of its value with $V_{u1} = 0$. In addition, R of the approximate method has the lower value with a higher decrease of 17.8%. Besides, the exact method computation reduced R to 87.6% and the approximate method calculation decreased R to 82.2%. Therefore, the difference in R is 5.4% in favor of the exact method. Comparing the α and V_{u1} cases using the exact method, the difference in R is 7.9% in favor of V_{u1} case.

Figure 6 reflects the variation of M_{1t} with α. It is clear that M_{1t} decreases gradually from 0.9118 to 0.4164 with α over α from 0 to 60º. For α = 60º, the decrease in M_{1t}, due to the applied positive α, is 54.33% of its value with α = 0º at ground conditions. Such decrease in M_{1t} is on the expense of 20.3% sacrifice in R. Figure 7 represents the change of M_{1t} with V_{u1}. It is clear that M_{1t} decreases gradually from 0.9118 to 0.4545 with V_{u1} over V_{u1} from 0 to 150 m/s. For V_{u1} = 150 m/s, the decrease in M_{1t}, due to the applied positive V_{u1}, is 50.15% % at ground conditions. Such decrease in M_{1t} is at the expense of 12.4% sacrifice in R. Thus, the difference in M_{1t} at the highest preswirl is 4.18% in favor of the α case while the difference in R is 7.9% in favor of the V_{u1} one.

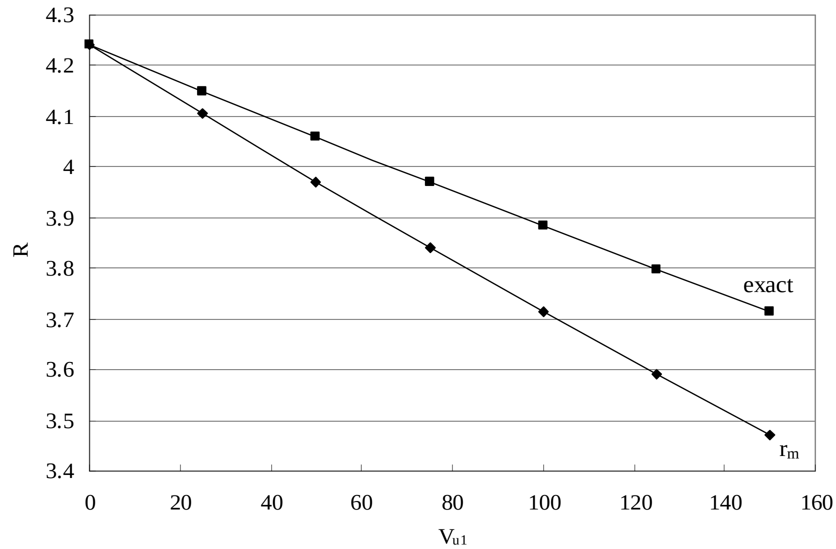


Fig. 5: Variation of R with V_{u1} for r_{1m} basis and exact methods.

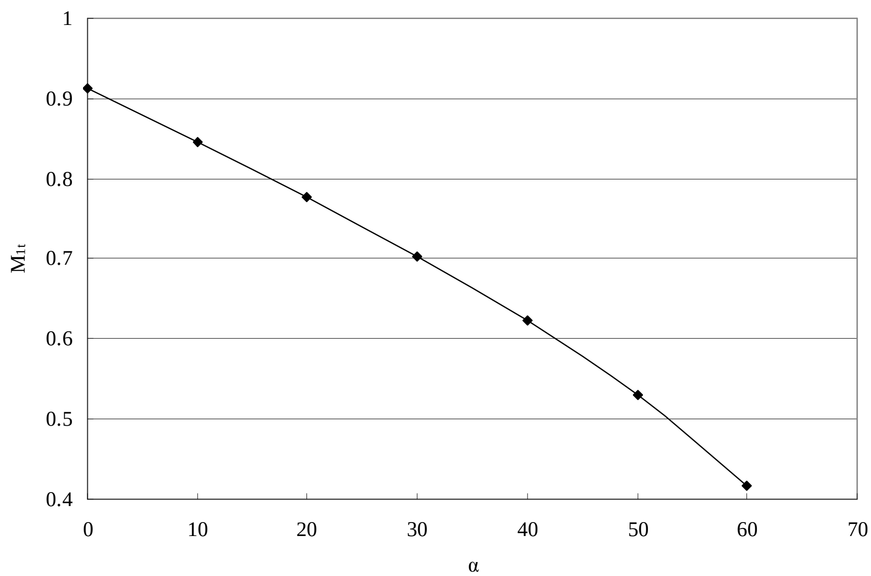


Fig. 6: Variation of M_{1t} with α.

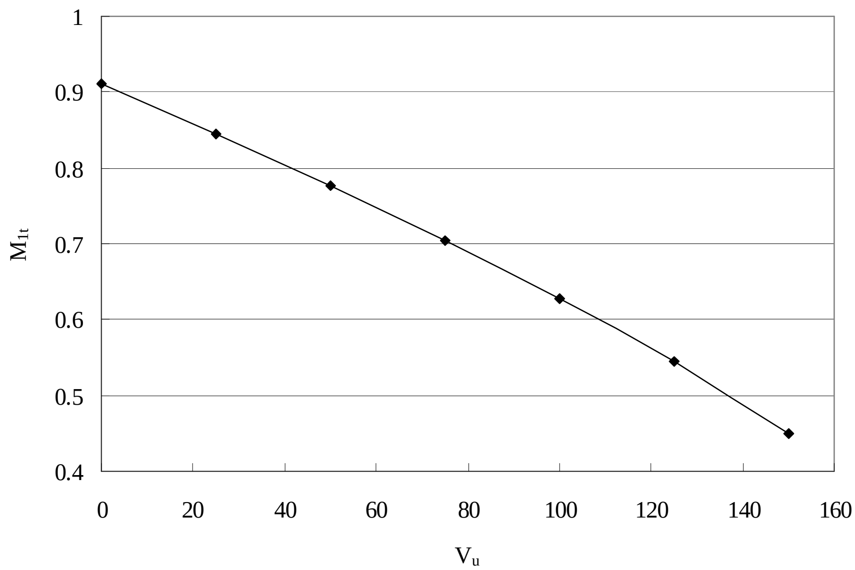


Fig. 7: Variation of M_{1t} with V_{u1}.

In the present study, M_{1t} without preswirl may be satisfactory for ground conditions. At 11000m flight altitude, T_{1t} decreases by 25% of its value at the ground (Najjar & Akeel 2002). Thus, at such altitude, M_{1t} increases to become 1.053 without preswirl. In addition, the flow distortion due to aircraft maneuvering may cause severe changes in the flow and, in turn, M_{1t} may increase even more. This may result in a significant impact on compressor stability and performance thus, a major decrease in M_{1t} must be achieved. At such high altitude, M_{1t} values with α = 60º and V_{u1} = 150 m/s become 0.4809 and 0.5187, respectively. Even at such high altitude, the decreased M_{1t} of both cases completely eliminates the compressibility effect at the impeller eye as well as avoids the formation of shocks. As a result, the operating conditions of aircraft engines become very safe and more stable even at such high altitude. The decrease in M_{1t} also reduces the performance deterioration due to elimination of shocks and consequent losses besides producing a much less noise pollution.

CONCLUSIONS

For a positive preswirl angle of 60º, the exact method decreased the normalized actual specific work to 81.4% and the approximate reduced it to 72.8% with a difference of 8.6% in favor of the exact method. For a positive preswirl velocity 150 m/s, the exact method reduced this work to 89% and of the approximate one decreased it to 83.5% with a difference of 5.5% in favor of the exact method. This difference using the exact method was 7.6% in favor of the preswirl velocity case.

For a positive preswirl angle of 60º, the exact method decreased the overall stagnation pressure ratio to 79.7% and of the approximate one reduced it to 71.4% with a difference of 8.3% in favor of the exact method. For a positive preswirl velocity 150 m/s, the exact method decreased such pressure ratio to 87.6% and of the approximate one reduced it to

82.2% with a difference of 5.4% in favor of the exact method. This difference using the exact method was 7.9% in favor of the preswirl velocity case.

For a positive preswirl angle of 60º, the decrease in the relative Mach number at impeller eye tip is 54.33% at ground conditions at the expense of 20.3% sacrifice in pressure ratio. For a positive preswirl velocity 150 m/s, the decrease in such Mach was 50.15% % on the expense of 12.4% sacrifice in pressure ratio. The difference in this Mach was 4.18% in favor of the positive preswirl angle case, while the difference in R was 7.9% in favor of the positive preswirl velocity.

The relative Mach number at impeller eye tip at 11000 m flight altitude is 1.053 (0.9118 at ground conditions) without preswirl. The flow distortion due to aircraft maneuvering may cause severe changes in the flow and such Mach may increase even more. This may cause a significant impact on compressor stability and performance. At that flight altitude, such Mach values for positive preswirl angle of 60º and velocity of 150 m/s become 0.4809 and 0.5187, respectively. The decreased Mach completely eliminates the compressibility effect and avoids the formation of shocks. Thus, the operating conditions of aircraft engines become very safe and more stable even at such high altitude. The present decrease in such Mach also reduces the performance deterioration due to elimination of shocks and consequent losses, besides a much less noise pollution. Therefore, this study reflects a significant effect of forced-vortex positive preswirl angle and velocity, at impeller eye, on centrifugal compressors performance at both ground and flight operating conditions.

NOMENCLATURE

C_p : mean specific heat at constant pressure, kJ/(kg.K)
C_v : mean specific heat at constant volume, kJ/(kg.K)
FIGVs : fixed inlet guide vanes
M_{1t} : relative Mach number at r_{1t}
N : impeller rotational speed, rps
P_{01} : stagnation pressure at r_1, kPa
P_{03} : stagnation pressure at diffuser exit casing, kPa
R : overall stagnation pressure ratio, P_{03}/P_{01}
R_0 : ideal gas constant, kJ/(kg.K)
r_1 : impeller eye local radius, m
r_{1m} : impeller eye mean radius, m
r_{1r} : impeller eye root radius, m
r_{1t} : impeller eye tip radius, m
r_2 : impeller exit radius, m
T_{1t} : static temperature at r_{1t}, K
T_{01} : stagnation temperature at r_1, K
U_1 : peripheral speed at r_1, m/s
U_{1t} : peripheral speed at r_{1t}, m/s
U_2 : impeller peripheral speed at r_2, m/s
V_1 : absolute velocity at r_1, m/s
V_{a1} : axial velocity at r_1, m/s
V_{a1m} : axial velocity at r_{1m}, m/s
V_{a1t} : axial velocity at r_{1t}, m/s

V_{u1} : preswirl velocity at r_1, m/s
V_{u1m} : preswirl velocity at r_{1m}, m/s
V_{u1t} : preswirl velocity at r_{1t}, m/s
V_{u2} : swirl velocity at r_2, m/s
W_1 : relative velocity at r_1, m/s
W_{1t} : relative velocity at r_{1t}, m/s
w : theoretical specific work, kJ/kg
w_A : actual specific work, kJ/kg
w_{A0} : actual specific work of the exact method for $\alpha = 0$, kJ/kg
w_{An} : normalized w_A, w_A / w_{A0}

GREEK SYMBOLS
α : preswirl angle, degrees
ΔT_0 : overall stagnation temperature difference, K
γ : specific heat ratio, C_p/C_v
η_c : compressor isentropic efficiency
σ : slip factor, V_{u2}/U_2
τ : theoretical specific torque, (kN.m.s)/kg
ω : angular velocity, s^{-1}
ψ : power input factor, dimensionless

SUBSCRIPTS
1m : station at impeller eye mean radius
2 : station at impeller exit

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