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A Study of Aerodynamic Performance of a Contra-Rotating Axial Compressor Stage

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ABSTRACT

This article presents an experimental investigation into the effect of speed ratio and axial spacing between contra-rotors on the aerodynamic performance of a contra-stage. The traverses of flow structure and pressure variation are examined at upstream and downstream of the first and the second rotor to illustrate the effect of speed ratio and axial spacing on the aerodynamic performance. The traverse results are analysed to obtain relative total head loss and blade element efficiency of the contra-rotors. The study reveals that the aerodynamics of a contra-stage is significantly affected by the speed ratio as well as the axial spacing between contra-rotors.

NOMENCLATURE

p static pressure
P total pressure
R radius
U peripheral velocity
V flow velocity
Y distance from hub, mm
α absolute flow angle
β relative flow angle
ρ density of air
ϕ_m flow coefficient
ψ_{Ts} inlet total to exit static pressure coefficient
ψ_s static pressure coefficient
ψ_t total pressure coefficient
ξ_{RI}, ξ_{RII} relative total head loss coefficients
η_{RI}, η_{RII} total-to-total blade element efficiency for the two rotors
η_{cs} total-to-total blade element efficiency for contra-stage

Subscripts

upstream of the first rotor
2 downstream of the first rotor
3 downstream of the second rotor
R_I value for first rotor
R_{II} value for contra-stage
x axial
m mean value

1. INTRODUCTION

In the recent years, there has been considerable interest in the aerodynamics of a contra-rotating axial flow compressor/fan stage, mainly due to its feasible application in future generation aircraft engines. Current trends of development of fuel-efficient aircraft engines for both civil and Detence applications point towards the use of contra-rotation in either an unducted or a ducted arrangement. Fuel savings of up to 30-40 per cent are now considered attainable due to the development of future ultra-high bypass turbo-fan engines, wherein a contra-rotating fan stage is being utilised in either an unducted or a ducted arrangement. In such a stage, the two rotors rotating in opposite directions are used without a stator in between[1,2] The drive for these rotors could be provided directly by a contra-rotating turbine or through a gear box[3,4]. The contra-stage in the above arrangements provides a much greater through flow capacity compared to a rotor-stator

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stage. The investigations carried out in a ducted contra-rotating compressor stage have further revealed that the contra-stage offers a significantly improved off-design performance, especially in the context of its rotating stall behaviour. It has been found that the severity of rotating stall is curtailed and the rotating stall is suppressed to lower flow rates[5,6]. This advantage of contra-rotation assumes an added significance in the context of improvement in the stability of the operation of a fan stage in the future generation ultra-high bypass turbo-fan engines. A nearly stall-free contra-rotating compressor stage also offers an attractive proposition for the development of an integrated multistage axial compressor incorporating both the contra-rotating as well as the conventional rotor-stator stages.

An examination of the effect of speed ratio and axial spacing between contra-rotors on the aerodynamics of a contra-stage is considered desirable to illustrate these important parameters on the performance of a contra-stage.

The present study reports an experimental investigation into the effect of speed ratio and axial spacing between contra-rotors on the aerodynamics of a contra-stage having a hub-tip ratio of 0.667. The flow and pressure traverses at upstream and downstream of the first and the second rotor for two axial spacings are reported for two speed combinations, viz, 1000-1000 and 1000-1500 rpm. The traverse results are analysed to obtain the relative total head loss coefficients and the blade element efficiencies.

2. TEST RIG AND INSTRUMENTATION

Experimental investigation has been carried out using a low speed contra-rotating axial compressor test rig, schematically shown in Fig. 1. The test compressor consists of a contra-rotating axial compressor stage having a hub-tip ratio of 0.667 and a tip diameter of 486 mm. The two rotors, each having 26 blades of 20° camber C-4 aerofoil sections, are independently driven by two thyristor-controlled 20 HP dc motors with a speed regulation up to 3000 rpm. The rotor blades, having a chord of 45 mm and an aspect ratio of 1.77, are set at 45° and 55° stagger angles, respectively. The air enters the test compressor through an inlet filter box into a bell mouth intake and is discharged to the atmosphere through a disc throttle valve installed at the end of the discharge duct.

The flow rate through the compressor is measured from the calibrated intake pressure drop. For this purpose, a pressure tapping in the inlet ducting, approximately 12 chords away from the leading edge of the first rotor, is used. The pressure rise across the first rotor and the stage is measured from the wall static pressure tappings. The traverses of the velocity, flow angle, total and static pressures are carried out using a calibrated three hole cobra yaw probe in null mode.

3. RESULTS AND DISCUSSION

Figures 2 and 3 show a typical velocity diagrams for the rotor-stator stage and the contra-stage. A comparison between the two reveals that in the contra-stage there is a significant improvement in relative velocity at the inlet of the second rotor (W_{2II}) due to its contra-rotation. This enhanced relative velocity is then directly diffused across the second rotor, thus providing a significant improvement in the stage pressure rise. Figure 4 reveals the compressor characteristics of the contra-stage employing a pair of contra-rotors each running at a speed of 1000 rpm and those of the rotor-stator stage having a rotor speed of 1500 rpm. The rotors are set with a small axial gap of the order of one-third of the blade chord. The

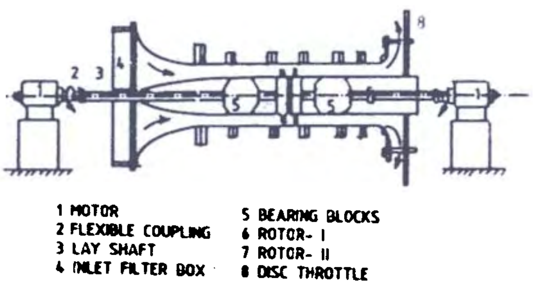

Figure 1. Schematic view of the test compressor.

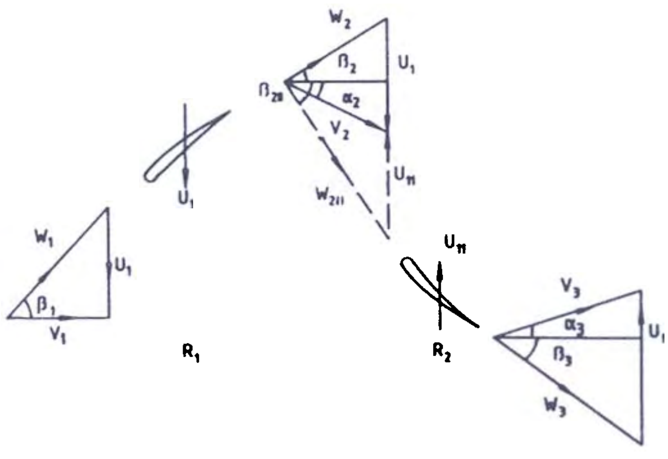

Figure 2. Velocity triangles for a contra-stage.

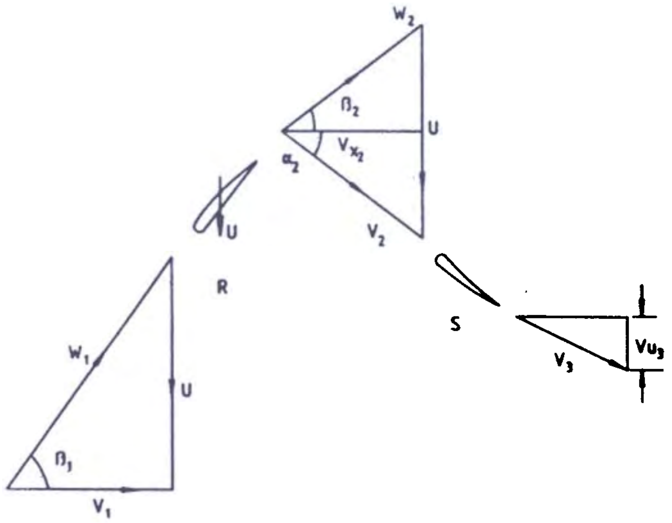

Figure 3. Velocity triangles for the rotor-stator stage.

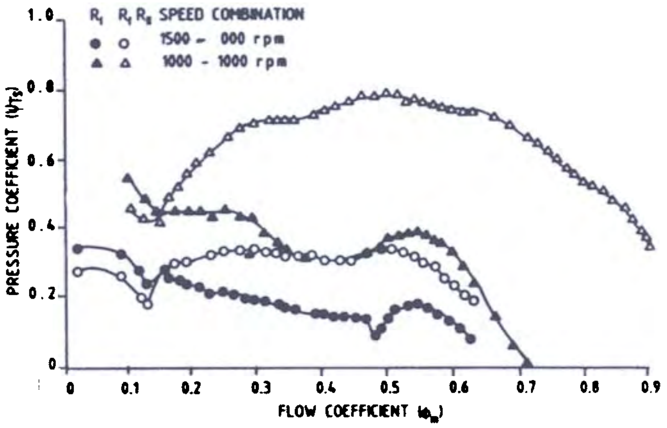

Figure 4. Compressor characteristics of a contra-stage and rotor-stator stage.

compressor characteristic is plotted in terms of the inlet total to exit static pressure rise coefficient ψ_{Ts}, based on mean peripheral speed of the first rotor and the flow coefficient (ϕ_m), based on the mean inlet axial velocity. It may be observed that the first rotor in both the arrangements stalls at the same flow coefficient, i.e., $\phi_m = 0.53$, while the contra-stage stalls at a lower flow coefficient, i.e., $\phi_m = 0.46$, as compared to the rotor-stator stage. The peak pressure rise development capacity (at the stall point) of a contra-stage is nearly 2.35 than that of the rotor-stator stage. It may further be noted from Fig. 4 that the peak value of $\psi_{Ts} = 0.34$, is attained by the rotor-stator stage and the contra-stage (rotor-rotor stage) at a flow coefficient of 0.50 and 0.90, respectively. The contra-stage thus provides an 80 per cent improvement in the through flow capacity.

Figure 5 shows the compressor characteristic curves for a contra-stage for two speed combinations, viz,

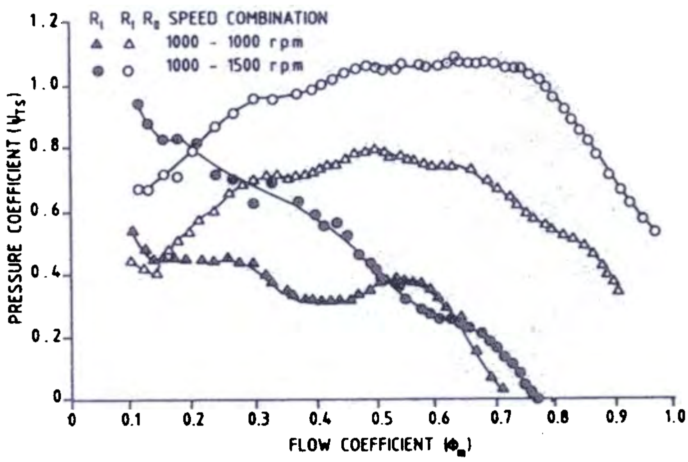

Figure 5. Effect of speed ratio of contra-rotors on the performance of a contra-rotating axial compressor stage, close axial gap case.

1000-1000 (speed ratio 1) and 1000-1500 rpm (speed ratio 1.5), respectively. It may be seen that for a speed ratio of 1.5, the first rotor as well as the contra-stage exhibit a significant improvement in terms of both the pressure rise and the flow coefficient as compared to the contra-stage having a speed ratio of unity. It may be noted that the contra-rotation of the second rotor in close vicinity of the first rotor at a speed faster (1.5 times) than the first rotor, enables the first rotor to operate with a negatively-slopped (stall-free) characteristics almost up to a flow coefficient of 0.12. Whereas, a positively-slopped characteristic was exhibited by this rotor for flow coefficients below 0.53, when the stage is operated with a speed ratio of unity. The contra-stage characteristic for a speed ratio of 1.5 exhibits a flat (zero-slopped) characteristic over a wider operating range, i.e., from $\phi_m = 0.75$ to $\phi_m = 0.46$. Table 1 gives stall points and corresponding values of ψ_{Ts} of the first rotor as well as for the contra-stage for two speed combinations.

Table 1. Effect of speed ratio (small axial gap)

Speed combination	First rotor (stall point)		Contra-stage (stall point)		Max. flow coefficient
(rmp)	ϕ_m	ψ_{Ts}	ϕ_m	ψ_{Ts}	
1000-1000	0.53	0.40	0.46	0.80	
1000-1500	no stall		0.45	1.05	

It may be seen from Table 1 that the peak ψ_{Ts} value for the contra-stage having a speed ratio 1.5, is 1.32 times higher than that for a speed ratio of unity and is nearly three times higher than that obtained using a rotor-stator stage (Fig. 4). It is also noted that an increase in the speed ratio results in an increase in the maximum flow coefficient from 0.90 to 0.97, thus improving the through flow capacity by 7.7 per cent.

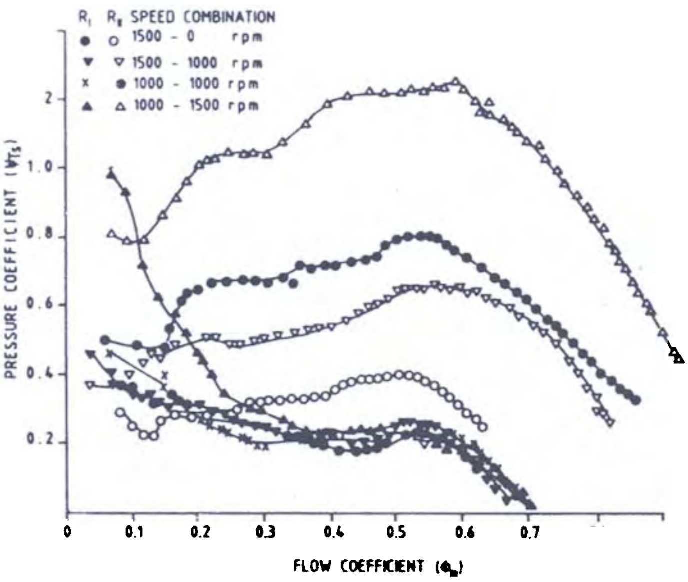

Figure 6. Effect of speed ratio of contra-rotors on the performance of contra-rotating axial compressor stage, large axial gap case.

Figure 6 shows the effect of speed ratio on the performance of the contra-stage for a large axial gap between contra-rotors (2 axial chords). The stall points and the respective values of ψ_{TS} for the first rotor and the contra-stage for different speed combinations are given in Table 2.

Table 2. Effect of speed ratio (large axial gap)

Speed combination (rpm)	First rotor (stall point)		Contra-stage (stall point)	
	ϕ_m	ψ_{Ts}	ϕ_m	ψ_{Ts}
1500-1000	0.54	0.27	0.54	0.65
1000-1000	0.53	0.27	0.55	0.80
1000-1500	0.48	0.26	0.59	1.25

It may be noted from Table 2 that the first rotor stall point is shifted towards a lower flow coefficient as the speed ratio is increased from 0.66 to 1.5. It is also noted that in a large axial gap case the contra-stage stall point has the tendency to shift towards a higher flow coefficient as the speed ratio between contra-rotors is increased. Whereas, in the small axial gap case a reverse effect has been observed.

3.1 Traverse Results

The traverses of flow structure and pressure variation across the compressor annulus have been carried out at upstream and downstream of the first and the second rotor for selected flow coefficients for the two speed combinations. The relative total head loss and the blade element efficiency variation across the annulus are derived from these traverse results.

3.2. Effect of Speed Ratio

Figure 7 shows the flow structure and pressure variation across the annulus of the contra-stage for the two speed combinations for a flow coefficient, $\phi_m = 0.7$. It may be observed that an increase in the speed ratio significantly affects the flow and pressure variation across the annulus at the exit of the first as well as the second rotor. At the exit of the first rotor, an increase in the speed ratio results in an improvement in the flow in the lower portion of the blade span. There is a notable decrease in flow angles a_2 and β_2 and an improvement in axial velocity V_{x2} in the lower portion of the blade span; however, in the upper portion of the blade span a reverse effect is observed. An increase in the speed ratio from 1 to 1.5 also affects the flow at the exit of the second rotor. Absolute flow angle, a_3 increases all along the blade height while the relative flow angle β_3 decreases in the lower portion of the blade but increases in the upper portion as the speed ratio is increased. The axial velocity at the exit of the second rotor V_{x3}, with increased speed ratio, exhibits an improvement in the lower portion of the blade while it deteriorates in the upper portion of the blade span. The variation of the static and total pressure rise coefficients ψ_s and ψ_t at the exit of the first and the second rotors shows a deterioration on nearly the entire blade span with an increase in the speed ratio. The deterioration in the pressure rise coefficients is, however, more pronounced in the lower portion of the blade height.

The variation of relative total head loss coefficients ζ_{RI} and ζ_{RII} across the annulus for the first and the second rotor respectively indicates that the total head loss increases all over the blade span as the speed ratio is increased from 1 to 1.5. It is seen from Fig. 7 that total-to-total blade element efficiency η_R of a contra-stage is also affected by the speed ratio of two contra-rotors. An increase in the speed ratio results in deterioration in the first rotor efficiency η_{RI} all along the blade height while the efficiency of the second rotor

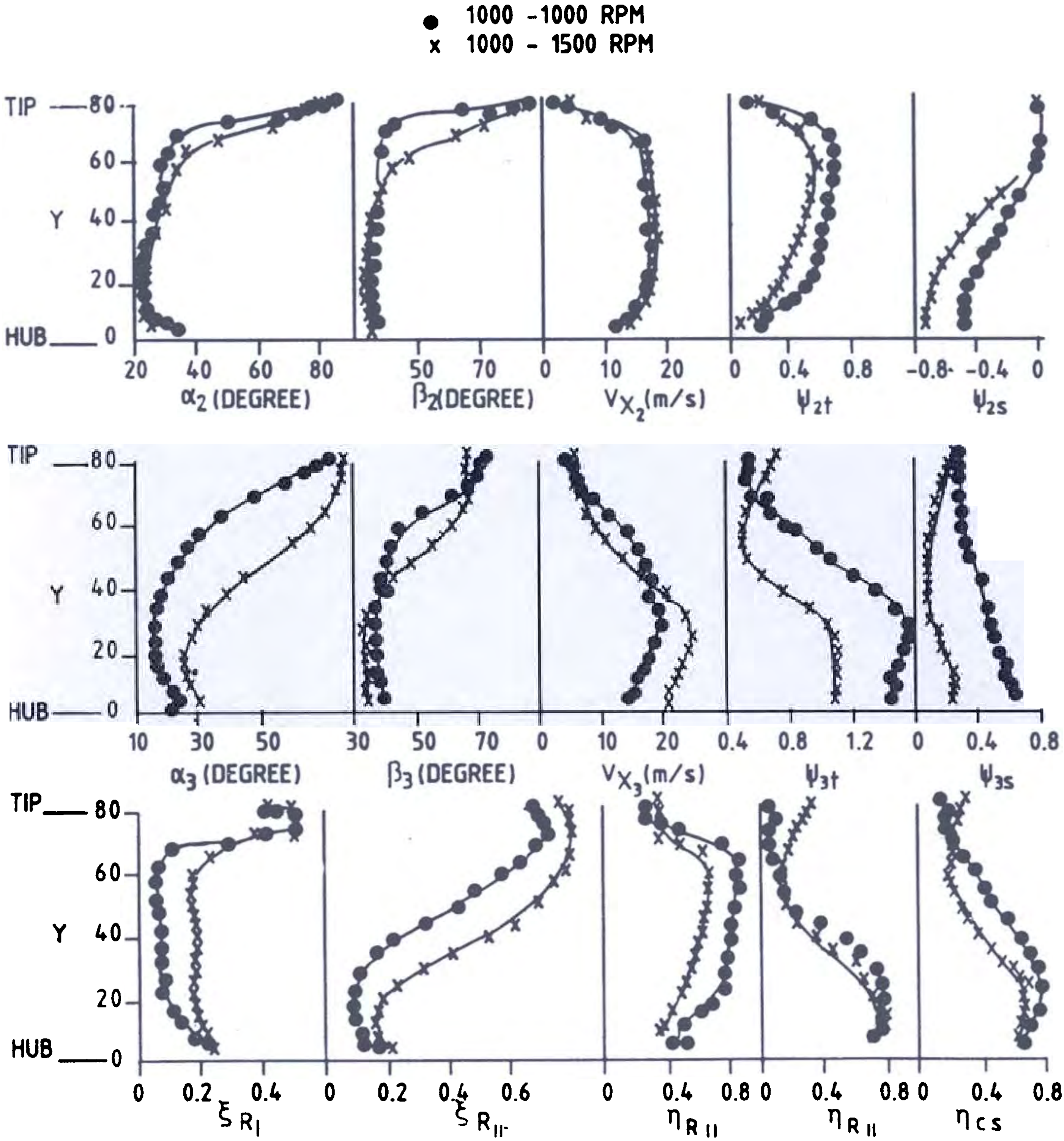

Figure 7. Speed ratio effect on traverse results ϕ_m = 0.7, close axial gap.

η_{RII} and in contra-stage deteriorates in the lower portion of the blade.

Figure 8 shows the flow structure and the pressure variation across the annulus of a contra-stage for the two speed combinations, for a flow coefficient of $\phi_m = 0.4$. It is noted that an increase in the speed ratio from 1 to 1.5 results in an improvement in the flow all along the blade height downstream of the first rotor.

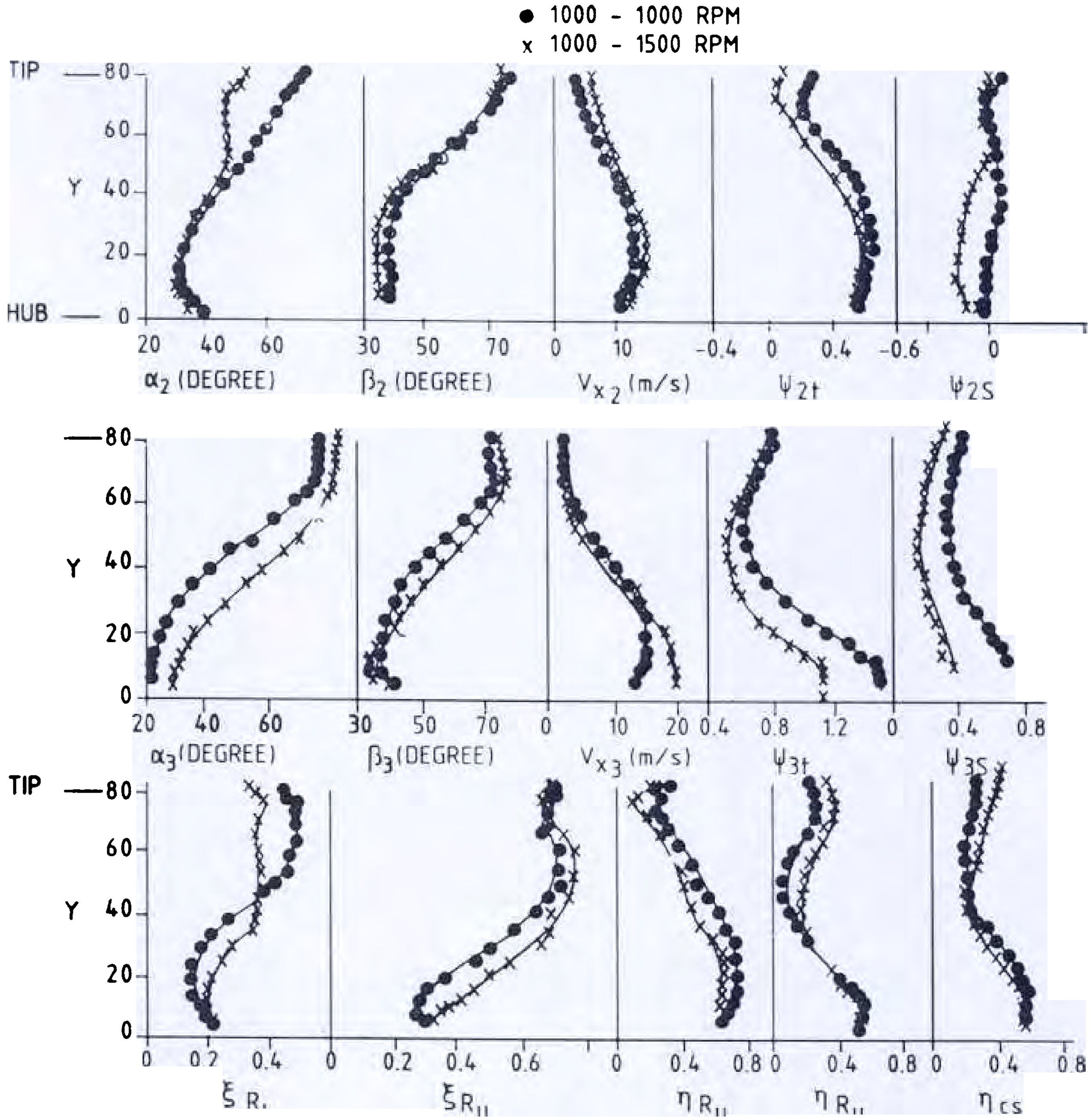

Figure 8. Speed ratio effect on traverse results ϕ_m = 0.4. $\phi_m = 0.40$

The speed ratio between contra-rotors also affects the flow at the exit of the second rotor. It may be seen that an increase in speed ratio from 1 to 1.5 results in an increase in the absolute flow angle all along the blade height while the relative flow angle decreases near the hub but increases in the upper portion of the blade span. The axial velocity V_{x3} is also increased near the hub with an increase in the speed ratio. However, no significant change in V_{x3} is observed in the upper portion of the blade span. The variation of static and total pressure rise coefficients ψ_s and ψ_t at the exit of the first and the second rotor shows a deterioration all along

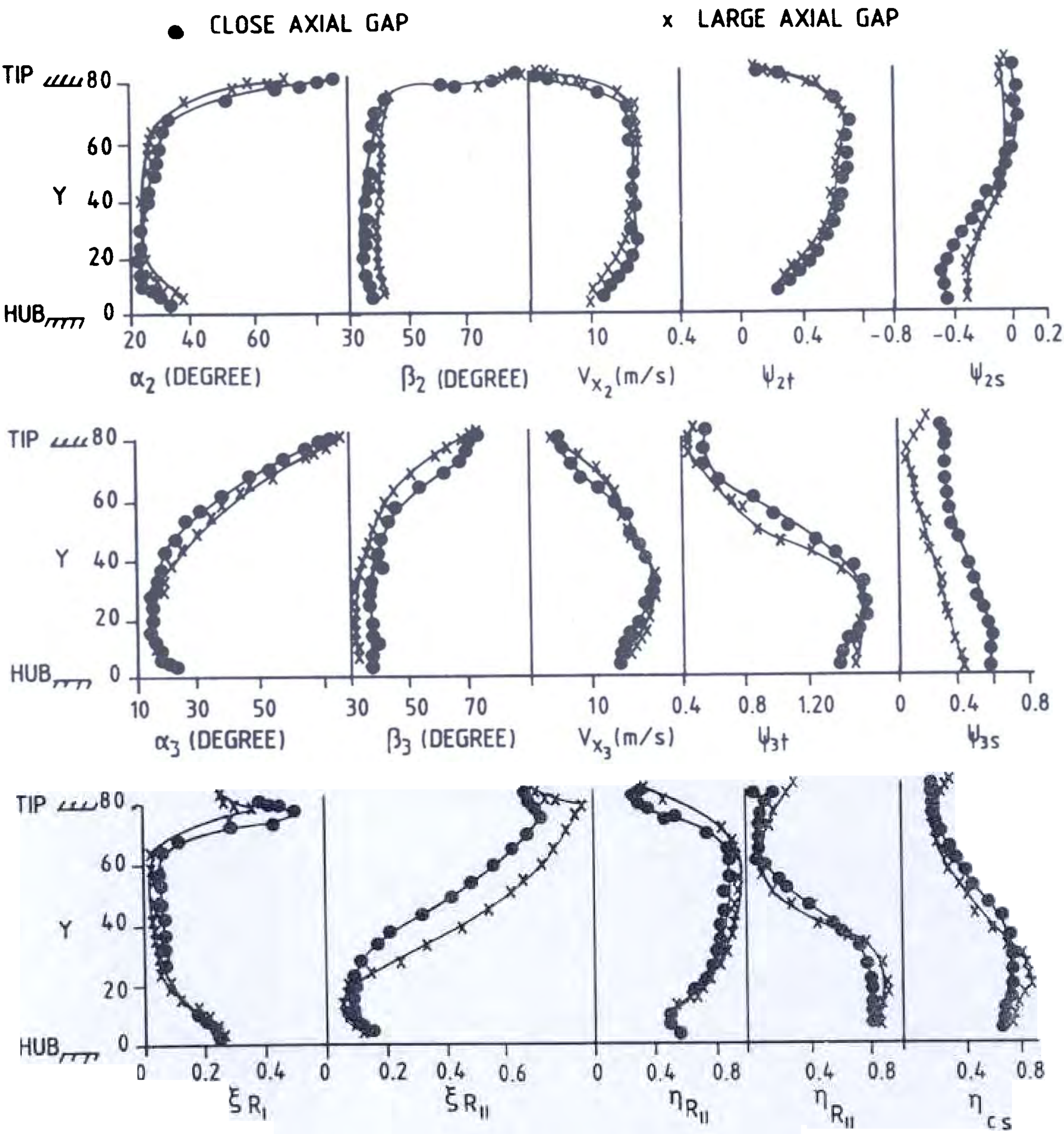

Figure 9. Axial spacing effect on traverse results, 1000-1000 rpm, $\phi_m = 0.7$

the blade height. The radial variation of the total head loss coefficients ξ_{RI} and ξ_{RII} for the first and the second rotor is also affected by the speed ratio. An increase in the speed ratio from 1 to 1.5 results in an increase in ξ_{RI} in the lower half portion of the blade span, while ξ_{RII} increases all along the blade height except near the tip where a decrease is evident.

The total-to-total efficiency for the first rotor η_{RI} decreases all along the blade height while η_{RII} and η_{cs}

increase only in the upper half portion of the blade span as the speed ratio is increased from 1 to 1.5.

3.3 Effect of Axial Spacing

Figure 9 shows the radial variation of flow and pressure quantities across the annulus for a speed combination of 1000-1000 rpm for two axial spacings, viz, small and large, for a flow coefficient of $\phi_m = 0.70$. It may be seen that at the downstream of the first rotor an increase in axial gap results in deterioration of V_{x2} in the lower half portion of the blade span, while in the upper part of the blade span a reverse effect is observed. An increase in axial gap also affects the flow at the exit of the second rotor. It may be seen that an increase in axial gap results in an improvement in the flow in the lower portion of the blade whereas the flow deteriorates in the upper half of the blade span. It is further noted that at the exit of the first rotor, ψ_{2t} deteriorates all along the blade height whereas ψ_{2s} improves in the lower portion of the blade span, with an increase in axial spacing. At the exit of the second rotor an increase in axial gap results in deterioration in ψ_{3s} and ψ_{3t} all along the blade height. The relative total head loss coefficient ξ_{RI} for the first rotor shows a decrease in its value all along the blade height except at a place very close to the hub. An increase in ξ_{RII} is observed all along the blade height with increased axial gap except in the close vicinity of the hub where a decrease in ξ_{RII} is noted in the case of large axial gap. The total-to-total efficiency of the first rotor, η_{RI} increases all along the blade height while the total-to-total efficiency for the second rotor, η_{RII} and for the contra-stage, η_{cs} deteriorates with an increase in axial spacing between the contra-rotors.

4. CONCLUSIONS

The results presented in the paper are limited to three speed ratios and two settings of axial gap. However, a fuller examination of factors affecting the stalled and unstalled performance of the contra-stage has been carried out [6,7]. The speed ratios of 1 and 1.5 are considered important for the contra-stage as the first one is suitable for direct drive of contra-rotors by contra-rotating turbine rotors while the second has been shown to significantly suppress stall to lower flows. The results presented have been limited to the selected speed ratio. The study is limited to two axial gaps primarily due to the limitations of the test set-up.

The main conclusions arrived at from the present study are:

(a) The speed ratio of the contra-rotors significantly affects the aerodynamic performance of the contra-stage. An increase in the speed ratio results in an improvement in the stage pressure rise and through flow capacity of the contra-stage.

(b) The stall point of the first rotor and the contra-stage is affected by the speed ratio of the contra-rotors. An increase in the speed ratio from 1 to 1.5 results in a shifting of stall point towards a lower flow coefficient.

(c) The axial spacing between contra-rotors significantly affects the aerodynamic performance of the contra-stage. The stall point of the first rotor and the contra-stage is shifted towards a higher flow coefficient as the axial spacing between contra-rotors is increased.

(d) The speed ratio between contra-rotors affects the flow structure across the annulus at downstream of the contra-rotors. At the downstream of the first rotor an increase in the speed ratio from 1 to 1.5 results in an improvement in flow structure in the lower half portion of the blade span.

(e) The radial variation of relative total head loss coefficients and blade element efficiency for contra-rotors and contra-stage is also affected by the speed ratio. An increase in the speed ratio results in an increase in relative total head loss coefficients for the two rotors.

(f) The blade element efficiency for the first rotor deteriorates all along the blade height while the efficiency of the second rotor and of the contra-stage increases in the upper half portion of the blade span as the speed ratio is increased.

(g) An increase in axial gap results in the deterioration of blade element efficiency in the lower half span of the first rotor while in the second rotor the efficiency deteriorates all along the blade height.

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