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A Study of Aeroacoustic Performance of a Contra-Rotating Axial Flow Compressor Stage

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ABSTRACT

The paper reports the results of an experimental investigation into the aeroacoustic performance of a contra-rotating axial flow compressor stage having a hub-tip ratio of 0.66. Aerodynamic superiority of a contra-stage is examined from the point of view of higher pressure rise, increased through flow and rotating stall suppression. Measurements of sound pressure level and real-time analysis of the noise signals is reported for different speed combinations for clean and distorted inlet flow for two axial gaps between the contra-rotors. The effect of pitch chord ratio and axial gap between the rotors on the aeroacoustic performance is discussed. The study reveals that the axial gap between the rotors significantly affects the aeroacoustic performance of a contra-stage.

NOMENCLATURE

c	blade chord
p	static pressure
P	total pressure
R_m	Mean rotor radius
s	pitch at mean radius

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U	mean peripheral velocity of the first rotor, ΩR_m
V_x	mean axial flow velocity
ϕ_m	mean flow coefficient V_x/U
ψ_{TS}	inlet total to exit static pressure rise coefficient $(p-p_t)/\frac{1}{2}\rho U^2$
Ω	angular speed of the first rotor
ρ	mass density

Suffixes

0	far upstream
1	first rotor inlet
2	first rotor exit
3	second rotor exit
R_1	value for first rotor
R_1R_2	value for contra-stage

1. INTRODUCTION

Current trends in the development of fuel efficient aircraft engines point towards the utilisation of contra-rotation in future ultra-high bypass turbofan engines[1,2]. Both un-ducted and ducted fan arrangements are being evaluated. The contra-rotating fan rotors in an aft-mounted fan engine may be directly driven by contra-rotating turbines, however in a front mounted contra-fan a geared drive is essential[3]. Bypass ratio of upto 40 is being considered achievable in an un-ducted fan (UDF) while a ducted contra-fan is being evaluated for a bypass ratio of 15-20. When compared with the current level of bypass of 6-8 in the present day turbofans, such an ultra-high bypass in future engines is considered important for substantial improvements in propulsive efficiency and reduction in specific fuel consumption. Fuel savings of upto 30 per cent are being claimed with UDF[4], while a ducted contra-fan is aimed at upto 15 per cent improvement in specific fuel consumption. Besides the above applications of contra-rotation in subsonic civil transport aircrafts, attempts are also underway to utilise contra-rotation in the development of 'hyper crisp' turbofan for a variable cycle engine for hypersonic air breathing propulsion system[5]. While these applications of contra-rotation offer a promise of improved propulsive efficiency, the excessive noise levels associated with such engines are of considerable importance.

Aerodynamic superiority of a contra-rotating axial flow compressor stage has been highlighted by Sharma, *et al*[6,7]. It was shown that besides a high through-flow capacity, a contra-stage provides a wider stall-free operation. Further, the aerodynamic performance of a contra-stage was shown to be dependent on a number of factors such as pitch-chord ratio, rotor staggers and axial spacing between the two rotors[7]. These parameters are also considered important from the point of view of aerodynamic performance of a contra-stage.

The present paper reports the results of an experimental investigation into the aeroacoustic performance of a contra- rotating axial compressor stage having a hub-tip ratio of 0.66. The effect of a number of factors including the presence of an inlet screen is examined. The present investigation is essentially a low speed test, however the results are considered important to highlight the significance of some of the factors which affect both the aerodynamic as well as aeroacoustic performance of a contra-stage.

2. TEST RIG AND INSTRUMENTATION

The test rig, schematically shown in Fig. 1 consists of a single stage of a contra-rotating axial flow compressor of hub-tip ratio of 0.66 having a tip diameter of 482 mm. The two rotors, each having 26 blades of C-4 aerofoil sections of 45 mm chord and 20 degrees of chamber are driven by thyrister-controlled DC motors at a speed between 0-2500 rpm. Stagger angle for the blades of the two rotors were set at 45 degrees. The air enters the test compressor through a bell mouth honey-combed intake and is discharged into the atmosphere through a disc throttle installed at the end of the exit ducting. The test facility provides for the variation of pitch chord ratio from 1.08 to 2.16 by changing the number of blades from 26 to 13 on each rotor. The axial spacing between the rotors is also varied from a small value of 1/3 chord to a

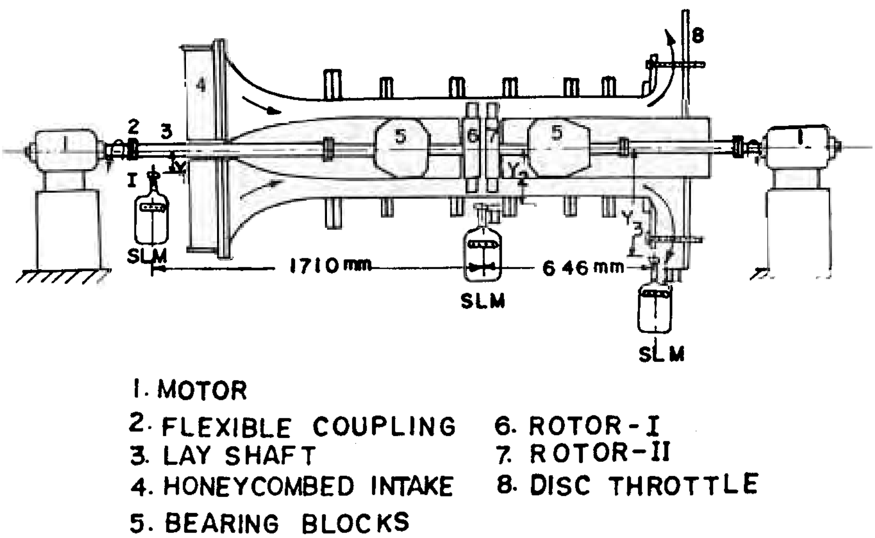


Figure 1. Schematic view of the test compressor.

large value of 2 axial chords. An inlet screen was installed in the inlet ducting approximately 8 chords upstream of the leading edge of the first rotor blades. The tests were carried out with and without the inlet screen.

The pressure rise across the rotors was measured from the wall static pressure tappings at appropriate locations in the machine. The flow rate through the stage was measured from the calibrated intake pressure drop. The sound pressure levels were measured using a portable B&K sound pressure level meter (SLM). The microphone positions at intake, in between the two rotors and at the exit of the machine are shown in Fig. 1. The linear frequency band was used for sound pressure level measurements at these locations. The signals from the SLM were analysed using an online A&D make real-time fast Fourier transform analyser. Frequency spectra so obtained were used to determine the predominant frequencies for different test cases.

3. RESULTS AND DISCUSSION

3.1 Aerodynamic Performance

Compressor pressure rise characteristics for 26-bladed rotor case for three speed combinations are shown in Fig. 2. In these plots the compressor pressure rise is expressed as ψ_{Ts} inlet-total to exit static pressure rise coefficient, flow coefficient ϕ_m being based on mean axial velocity. It may be noted that the speed ratio of the two

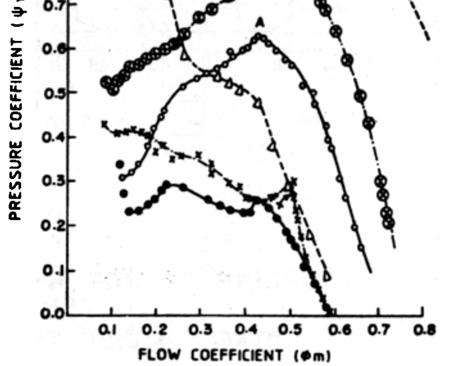


Figure 2. Compressor characteristic for three contra-speed combinations, 26-bladed rotors, 45/45 degree stagger case.

rotors significantly effect the performance of the first rotor R_1 as well as that of the contra-stage R_1R_2. It may be observed that the pressure rise characteristic of the first rotor for a speed ratio of 1.5 i.e., 1500-2250 rpm case, exhibits a continuously rising characteristic, while a break is evident for speed ratios of 0.66 and 1. The contra-stage performance is also considerably improved when the two rotors are run at a speed combination of 1500-2250 rpm. The peak inlet total to exit static pressure rise coefficient for the contra-stage for this speed combination is around 0.93 which is almost three times that produced by a rotor-stator stage in which the second rotor was held stationary. The signals from hotwire anemometers also confirmed that rotating stall was completely suppressed in a contra-stage operating with a speed ratio of 1.5.

Tests with increased pitch-chord ratio using 13-bladed rotors also confirmed the above improvement in contra-stage performance as shown in Fig. 3. It may be seen that the first rotor in a contra speed combination of 1500-2250 rpm case exhibits a steep negatively sloped characteristic all the way upto a low flow coefficient of 0.1.

The above improvement in stalling performance of a contra-stage is comparable with the improvement obtainable in a rotor-stator stage using an anti-stalling device, as can be seen[8] from Fig. 4.

3.2 Acoustic Performance

3.2.1 Sound Pressure Level Measurements

Figure 5 shows the variation of sound pressure level (SPL), with flow coefficient ϕ_m for different speed combinations at stations I, II and III respectively for 26-bladed

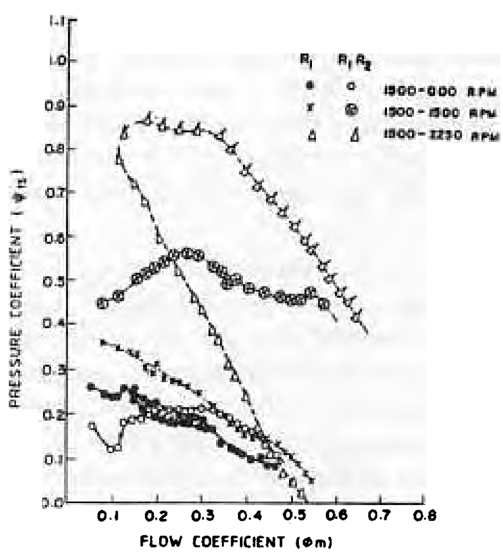


Figure 3. Compressor characteristic for three contra-speed combinations, 13-bladed rotors, 45/45 degree stagger case.

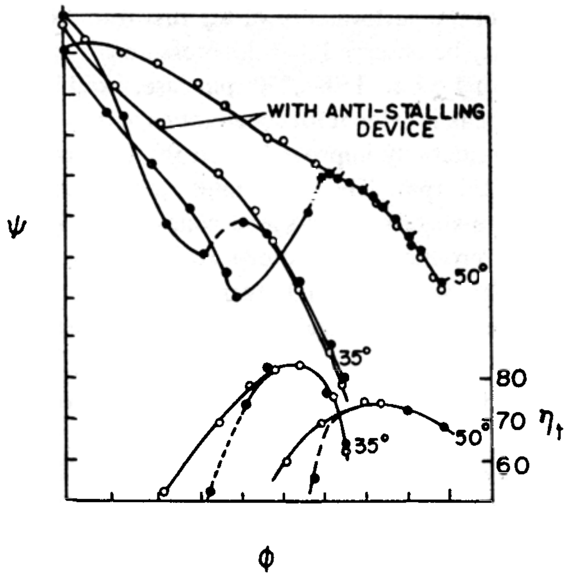


Figure 4. Axial fan performance characteristic with and without anti-stalling device[8].

rotor case. The SPL values in these plots refer to the net SPL obtained after subtracting the background noise from drive motors, etc.

At the intake of the test compressor, it may be observed that the SPL initially increases with the decrease in the flow coefficient, attaining a peak value, thereafter decreasing upon further reduction in flow coefficient. The peak SPL value varies with the speed combination, from 97 dB for a rotor-stator case (1500-000 rpm) to 117 dB for a contra-speed combination of 1500-2250 rpm. The flow coefficient corresponding to peak SPL is also affected by the speed ratio of the two rotors. The locus of peak SPL point at the inlet of the test machine for different speed combinations is also shown in Fig. 5.

The variation of SPL at a location midway between the contra-rotors (station II) is shown in Fig. 5 for different speed combinations. It may be noted that for a rotor-stator arrangement (1500-000 rpm) the SPL initially rises with the decrease in flow coefficient attaining a peak of 118 dB, thereafter decreases with further reduction in flow rate. The acoustic behaviour of contra-rotors is however markedly different in that the SPL initially remains constant upto a flow coefficient of 0.5, increasing thereafter with the decrease in flow rate to a peak value and operating around this high value under off design conditions. The peak SPL value varies with the operating speed ratio of the contra-rotors. It may be noted that a peak SPL value of 130 dB is recorded for a speed combination of 1500-2250 rpm as against 108 dB for a rotor-stator stage (1500-000 rpm).

The measurements of SPL at the exit of the contra-stage (station III) shown in Fig. 5 also exhibit the variation of SPL with flow coefficient as well as the contra-speed combination. The peak SPL of 132 dB has been measured at this location for a speed ratio of 1.5 as against 114 dB for rotor-stator stage. The peak SPL values at stations I, II and III for different speed combinations for contra-stage are given in Table 1. It may be noted that SPL is attenuated towards the intake while it is amplified towards the exit. Further, the amplification of noise level towards the exit of the compressor varies with the contra-speed ratio, beiag the lowest (2 dB) for 1500-2250 rpm case. It is remarkable that while the contra-stage shows a significant improvement in aerodynamic performance for a speed ratio of 1.5, the peak SPL values for this speed ratio at stations II and III are as high as 132 dB.

Table 1. **Peak SPL values for different speed combinations for contra-stage**

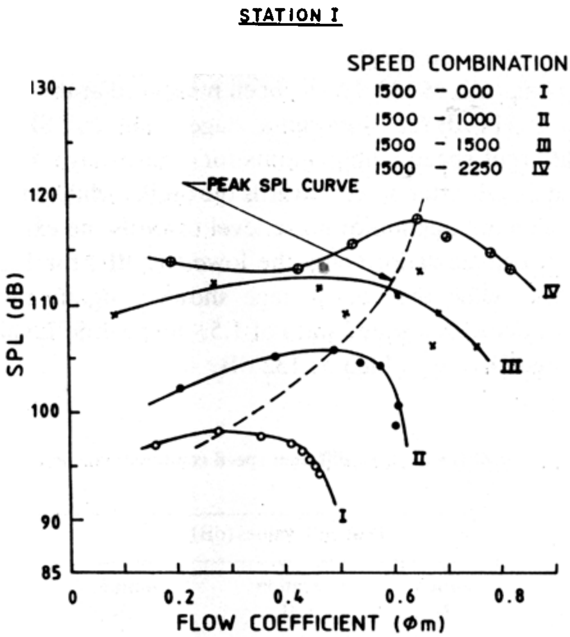
Speed combination (rpm)	Peak SPL values (dB)			% amplification from II to III
	Station I	Station II	Station III	
1500-000	97	108	114	6.54
1500-1000	104	114	125	9.65
1500-1500	111	120	128	6.66
1500-2250	117	130	132	1.54

3.2.2 Effect of Pitch-Chord Ratio

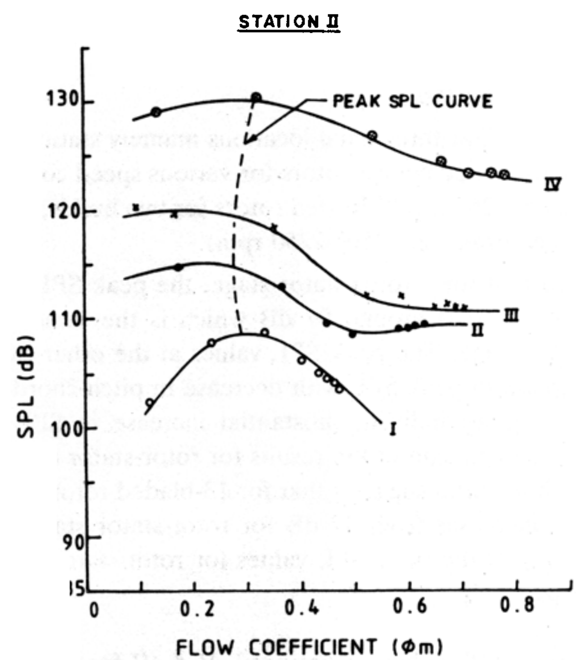
Measurement of SPL at three axial locations mamely stations I, II and III were also carried out for 13-bladed contra-rotors for various speed combinations. Figure 6 shows the results for the 26- and 13-bladed rotors for two builds, namely, rotor-stator (1500-000 rpm) and contra-stage (1500-2250 rpm).

It may be noted that for a rotor-stator stage, the peak SPL measured at intake for a 13-bladed rotor case is around 97 dB which is the same as measured for a 26-bladed rotor-stator stage. The peak SPL values at the other two stations (II and III) indicate an increase in peak SPL with decrease in pitch-chord ratio. The results for a contra-stage (Fig. 6) indicate substantial increase in SPL with decrease in pitch-chord ratio. A comparison of the results for rotor-stator and contra-rotor stage for the same pitch-chord ratio suggests that for 13-bladed rotor case ($s/c = 2.16$) the peak SPL at intake increases from 97 dB for rotor-stator stage to 112 dB for the contra-stage. At the exit, the peak SPL values for rotor-stator and contra-stage are 116 and 126 dB respectively.

Table 2. gives peak SPL values at stations I, II & III for two speed combinations for 26- and 13-bladed rotors.


STATION I
SPEED COMBINATION
1500 – 000 I
1500 – 1000 II
1500 – 1500 III
1500 – 2250 IV
PEAK SPL CURVE
SPL (dB)
130
120
110
100
90
85
0
0.2
0.4
0.6
0.8
FLOW COEFFICIENT (Φm)
I
II
III
IV

(a)


STATION II
PEAK SPL CURVE
SPL (dB)
130
120
110
100
90
15
0
0.2
0.4
0.6
0.8
FLOW COEFFICIENT (Φm)
I
II
III
IV

(b)

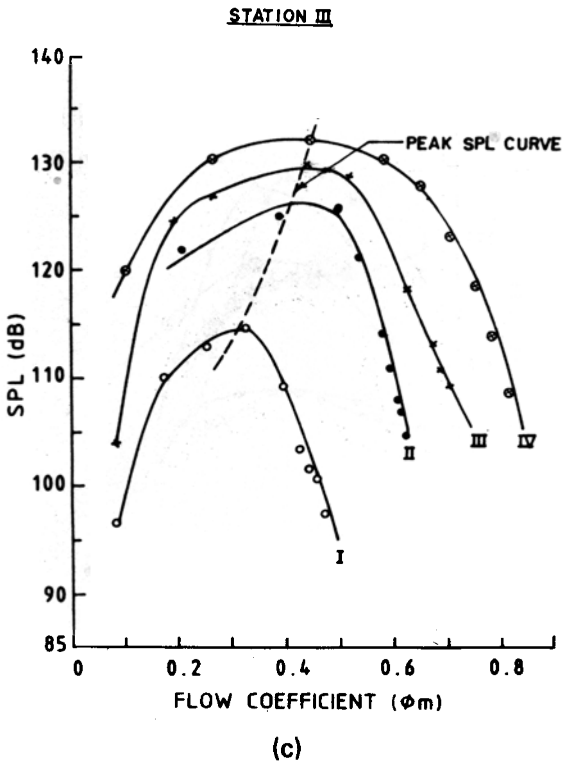


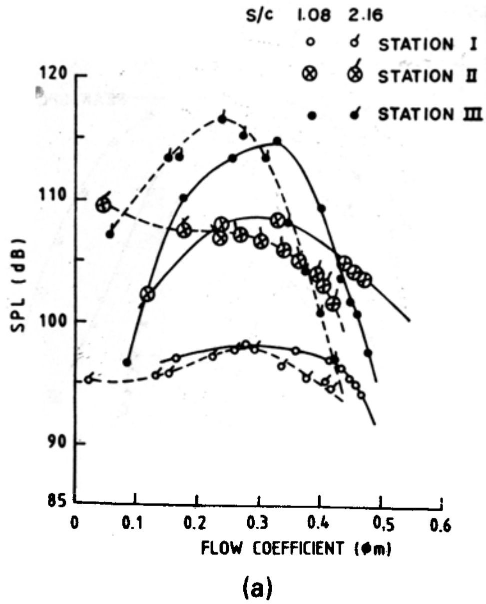
Figure 5. Variation of sound pressure level of three axial locations for different speed combinations for a contra-stage.

Table 2. Peak SPL values for two speed combinations for 26- and 13-bladed rotors

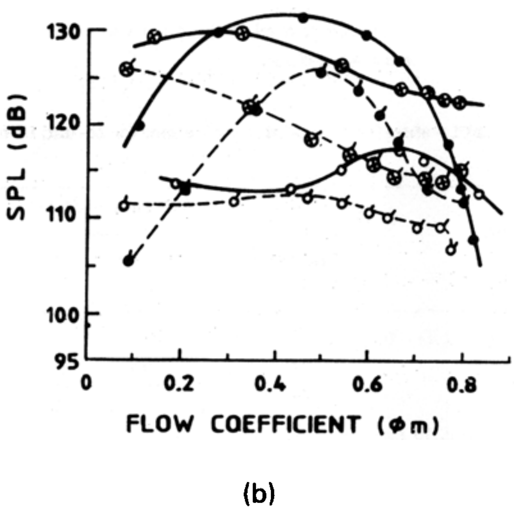
Pitch-chord ratio	Peak SPL values (dB)		
	Station I	Station II	Station III
Rotor-stator stage: 1500-000 rpm			
1.08	97	108	114
2.16	97	107	116
Contra-stage: 1500-2250 rpm			
1.08	117	130	132
2.16	112	126	126

3.2.3 Effect of Upstream Screen

Figure 7 shows the effect of an upstream screen on SPL for rotor-stator as well as a contra-rotor stage. The measurements of SPL are presented at three axial locations for the above two builds. It may be seen that at the intake the presence of upstream



(a) Rotor-stator stage, 1500-000 rpm.



(b) Contra-stage, 1500-2250 rpm.

Figure 6. Effect of pitch chord ratio on SPL for a rotor-stator and a contra-stage.

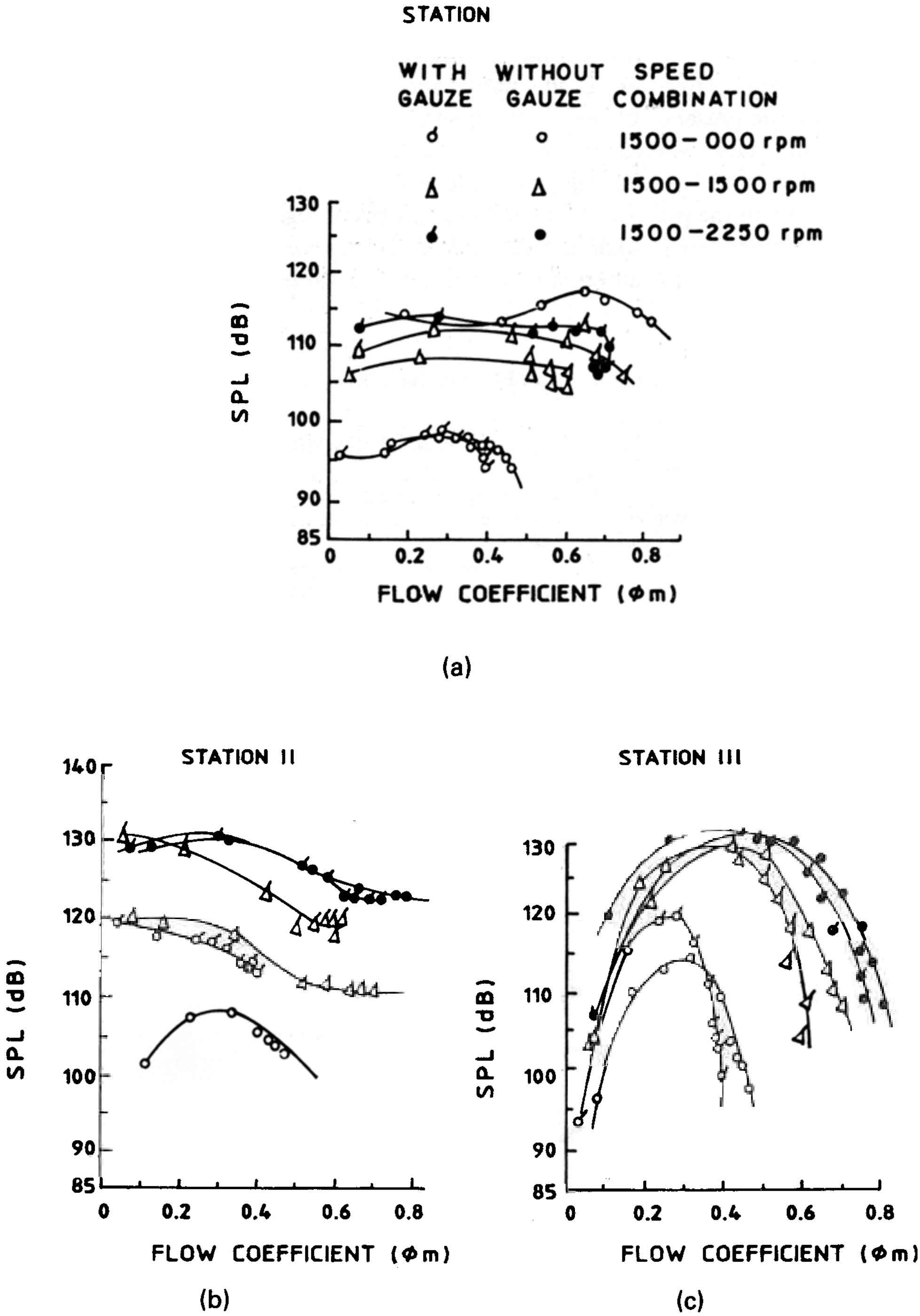


Figure 7. **Effect of inlet gauze on sound pressure level for different speed combinations of a contra-stage.**

screen results in a small decrease in peak SPL from about 117 to 113 dB for the contra-stage (1500-2250 rpm) while no significant change is noticeable for the rotor-stator stage. However, at an axial location midway between the contra-rotors (station II), the presence of the upstream screen does not alter the peak SPL value for the contra-stage, whereas, a substantial increase in peak SPL, from 108 to 119 dB is observed for a rotor-stator stage. Sound level measurements at the exit (station III) also indicate that the presence of the inlet screen has no significant effect on the peak SPL from a contra-stage while a 5 dB increase is observed for a rotor-stator stage. The peak SPL values for different cases are given in Table 3.

Table 3. Peak SPL values for different cases

Speed combination (rpm)	Peak SPL values (dB)					
	Without inlet gauze			With inlet gauze		
	Station I	Station II	Station III	Station I	Station II	Station III
1500-000	97	108	114	97	119	119
1500-2250	117	130	130	113	130	129

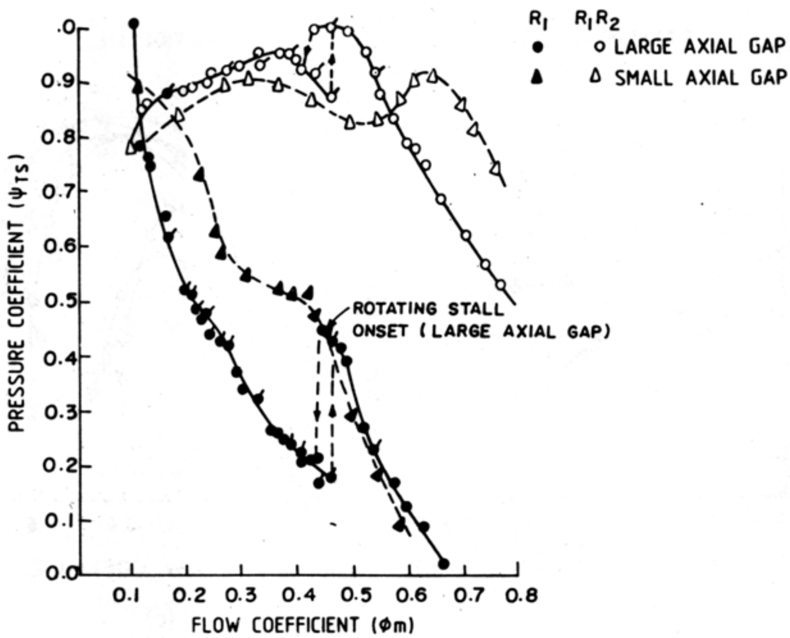
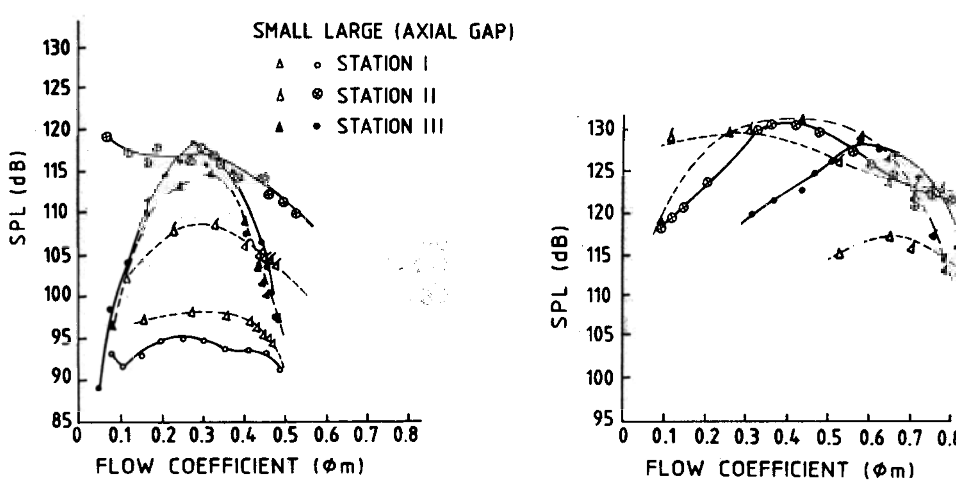


Figure 8. Effect of axial spacing between the rotors on contra-stage performance for speed combination of 1500-2250 rpm.

3.2.4 Effect of Axial Gap Between the Rotors

The axial gap between the two rotors significantly affects both the aerodynamics and acoustic performance of a contra-fan stage as is evident from Figs. 8 and 9. In Fig. 8, the pressure rise characteristics are shown for two settings of axial gap, namely, small (1/3 chord) and large (2 chords). The performance of the first rotor (R_1) and that of the two contra rotors combined (R_1R_2) is plotted in this graph. It is evident that increase in axial gap between the rotors results into an abrupt type of stall as the flow rate is reduced to a point A, marked on the characteristic. The recovery from stall is associated with a small hysteresis. The steep throttle lines at stall onset and recovery in this case are a consequence of contra-rotation of the adjacent rotor which acts like a slave fan thus providing down stream suction for the first rotor. It is therefore, noted that the unique advantage of contra-rotation of suppressing rotating stall is lost if the second rotor is placed too far away from the first rotor.

The axial gap between the two blade rows also significantly influences the sound pressure levels for a rotor-stator as well as a contra-stage as may be seen from Fig. 9. The peak SPL values for rotor-stator and rotor-rotor (contra-stage) for two axial gaps are shown in Table 4. It may be noted that in a rotor-stator stage, an increase in axial gap from small (1/3 chord) to large (2 chord) results in a reduction of 3 to 4 dB in the peak SPL at intake and exit of the test compressor. In the case of a contra-stage operating with a speed ratio of 1.5, an increase in axial gap from small to large results in a reduction in peak SPL of 10 dB at the intake and 5 dB at the exit. This reduction in peak SPL for large gap case is thought to have been linked with the detuning of blade passing frequencies in a contra-stage when the two rotors are placed far apart as may be seen from the spectrum results in Fig. 10. For small axial gap case, the predominant frequency of 1550 Hz at the exit for a contra-stage is close to the sum of blade passing frequencies of the two rotors whereas for the large axial gap case no



(a) Rotor-stator stage, 1500-000 rpm. (b) Contra-stage, 1500-2250 rpm.

Figure 9. Sound pressure level for two axial gaps for a rotor-stator and a contra-stage.

such compounding of frequencies is observed. It is thus evident that an increase in axial gap while degrading the aerodynamic performance results in improvement in acoustic performance of the contra-fan stage. A trade off between aerodynamic and acoustic performance may have to be carried out at the design stage.

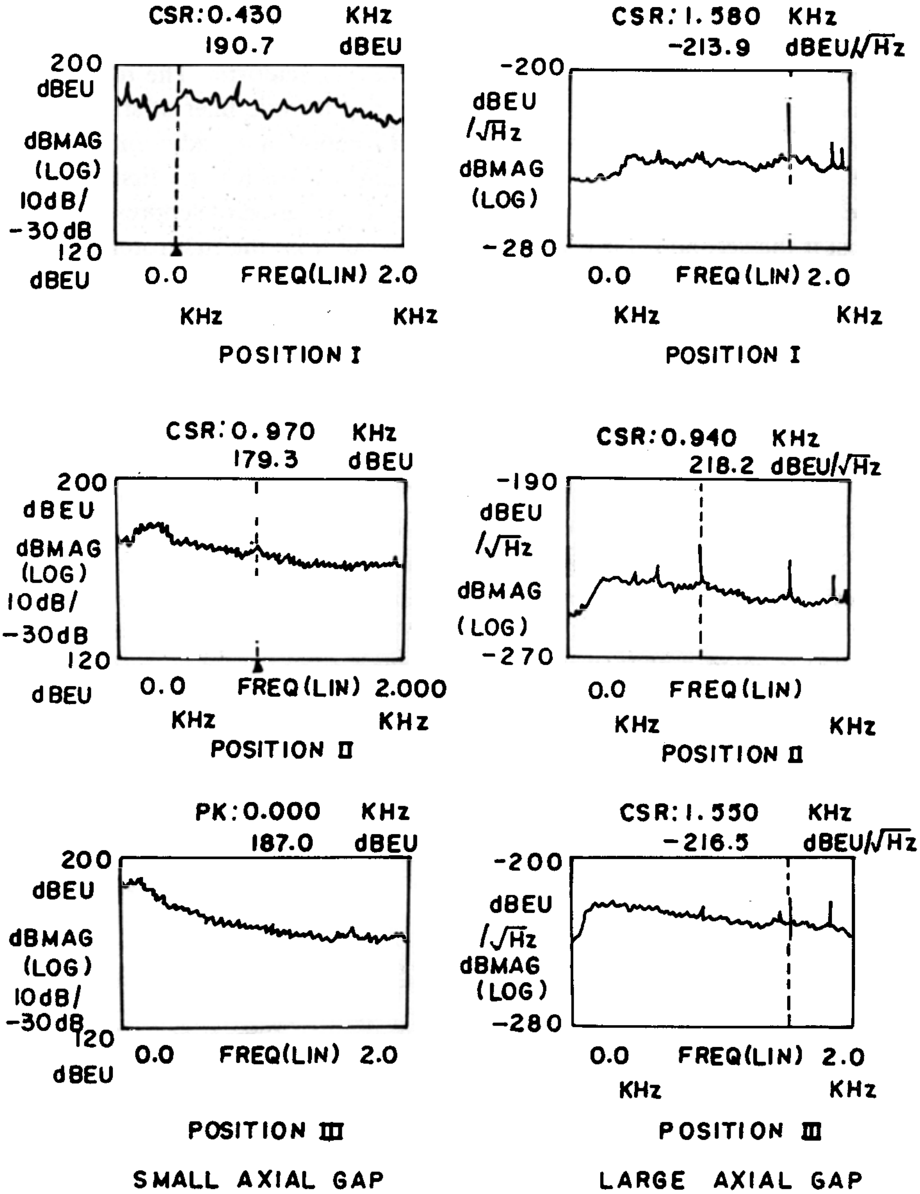


Figure 10. Noise spectrum at three axial locations for two axial gap settings, speed combination 1500-2250 rpm.

Table 4. Peak SPL values for rotor-stator and rotor-rotor for two axial gaps

Axial gap	Peak SPL values (dB)		
	Station I	Station II	Station III
Rotor-stator Stage: 1500-000 rpm			
Small	97	108	114
Large	94	117	118
Contra-stage: 1500-2250 rpm			
Small	117	130	132
Large	107	131	127

4. CONCLUSIONS

The following major conclusions are drawn from the present study:

(a) A ducted contra-stage produces a superior aerodynamic performance when the contra-rotors are placed with small axial gap between them;

(b) The aerodynamic superiority of a ducted contra-stage is associated with excessive noise levels. SPLs are affected by a number of factors including pitch-chord ratio, speed ratio and axial gap between the rotors;

(c) The presence of an inlet wire gauze has been found to increase the discharge SPLs by 5 dB for a rotor-stator stage whereas no significant change was observed for a contra-fan stage; and

(d) The axial gap between the rotors significantly affects the aeroacoustic performance of a contra-stage. The real-time analysis of sound signals has revealed that the excessive noise levels for closely spaced contra-rotors are associated with the direct compounding of blade passing frequencies, the frequency compounding being absent if the rotors are placed far apart resulting into significant reduction in noise levels.

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