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Cascade Tests of High Stagger Compressor Blades*

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The aim of this report is to obtain the two-dimensional performance of compressor cascade with high stagger.

The results are as follows:

- 1) The test method to obtain two-dimensional performance of compressor cascades has been determined.
- 2) The tests were carried out successfully and the performances of compressor cascades were obtained for 31 combinations of the pitch chord ratio $S/C=0.7, 1.0, 1.2$, and the stagger angle $\xi=45^\circ, 50^\circ, 60^\circ, 65^\circ$ to each of the camber $C_{l_0}=0.0, 0.4, 0.8, 1.2$.
- 3) The design points were selected and the design loading limits were derived from the cascade data.

1. Introduction

High stagger compressor blades have been used in the blower for a long time. Hitherto the cascade performance was determined from the single blade performance which was modified theoretically and experimentally. But it could not indicate the optimum design value, nor the maximum loading limit of the cascade.

A number of two-dimensional cascade tests had been made previously. But the performance of high stagger compressor blades was not established correctly.

On the other hand, the high stagger compressor blades are used in the axial blower with low pressure ratio, in the tip region of the first stage and the rear stage with low axial velocity in the multi-stage axial flow compressor.

Then it is important to obtain the performance of the cascade.

2. Designation of the cascade performance

2.1 Symbols

According to Fig. 1, we define the symbols in this report as follows.

- α_1 : inlet air angle, deg
 α_2 : outlet air angle, deg
 $\Delta\alpha$: deviation angle from average outlet air angle, deg

- α_∞ : vector mean angle, deg
 C_{l_0} : camber
 ξ : stagger angle, deg
 $\varepsilon = \alpha_1 - \alpha_2$: turning angle, deg
 $i = \alpha_1 - \xi$: incident angle, deg
 S : pitch, mm
 s : time, sec
 C : chord length, mm
 ρ : density of air
 P_1 : inlet total pressure, abs
 P_2 : outlet total pressure, abs
 P_{2l} : local value of the outlet total pressure, abs
 p_1 : inlet static pressure, abs
 p_2 : outlet static pressure, abs
 p_{2l} : local value of static pressure on the blade surface, abs
 V_1 : inlet velocity
 V_2 : outlet velocity
 V_{1a} : axial velocity of inlet flow
 V_{2a} : axial velocity of outlet flow
 V_{2al} : local value of axial velocity of outlet flow
 V_∞ : vector mean velocity
 V_{W1} : tangential velocity of inlet flow
 V_{W2} : tangential velocity of outlet flow
 $\bar{\omega}_p$: mean total pressure loss between the two blades
 ζ : total pressure loss coefficient
 L : lift force
 D : drag force
 D_p : profile drag force
 C_L : lift coefficient
 C_{Dp} : profile drag coefficient
 $C_{s1} = (p_{2l} - p_1) / (P_1 - p_1)$: pressure coefficient on the blade surface

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x : spanwise direction

y : cascade direction

z : outlet flow direction

n : number of blades

η_{br} : blade element efficiency of the cascade

Δp_r : experimental static pressure rise across the cascade

$\Delta p_{thr} = \frac{1}{2} \rho (V_1^2 - V_2^2)$: theoretical static pressure rise across the cascade

2.2 Designate method of cascade performance

2.2.1 Inlet angle and outlet angle

Inlet air angle is constant in front of the cascade in wind tunnel, but outlet air angle frequently shows a deviation of a few degrees along one pitch as shown in Fig. 2.

In this case, we used the arithmetic mean value as the value of outlet air angle. Because the value is equal to the value which is calculated from the momentum and continuity equations.

2.2.2 Total pressure loss coefficient

Fig. 1. Symbols of the cascade

Fig. 2 Measured results

The characteristics of the outlet air flow were measured by the 5 mouth arrow-head type pitot tube at the mid-span of central blade along the cascade. Fig. 2 shows one of the examples. Total pressure loss $\bar{w}_p$ of the two-dimensional performance is a mean value of the total pressure loss along the pitch of the mid-span. Therefore it is defined as follows.

$$\bar{w}_p = \frac{1}{S} \int_0^S (P_1 - P_{2l}) dS$$

Total pressure loss coefficient is defined as follows

$$\zeta = \frac{\bar{w}_p}{P_1 - p_1} = \frac{\bar{w}_p}{\frac{1}{2} \rho V_1^2}$$

2.2.3 Lift coefficient and profile drag coefficient

These coefficients are determined from the following equations using the vector mean angle α_∞ .

$$\tan \alpha_\infty = \frac{1}{2} (\tan \alpha_1 + \tan \alpha_2)$$

$$C_{Dp} = \frac{S}{C} \frac{\bar{w}_p}{\frac{1}{2} \rho V_\infty^2} \cos \alpha_\infty = \frac{S}{C} \cdot \frac{\bar{w}_p}{\frac{1}{2} \rho V_1^2} \cdot \frac{\cos^3 \alpha_\infty}{\cos^2 \alpha_1}$$

	Thickness distribution	Camber height	Camber gradient
x	y_u, y_l	y	dy/dx
0	0	0	—
0.5	0.772	0.250	0.421 20
0.75	0.932	0.350	0.388 75
1.25	1.169	0.535	0.347 70
2.5	1.574	0.930	0.291 55
5.0	2.177	1.580	0.234 30
7.5	2.647	2.120	0.199 95
10	3.040	2.585	0.174 85
15	3.666	3.365	0.138 05
20	4.143	3.980	0.110 30
25	4.503	4.475	0.087 45
30	4.760	4.860	0.067 45
35	4.924	5.150	0.049 25
40	4.996	5.355	0.032 25
45	4.963	5.475	0.015 95
50	4.812	5.515	0
55	4.565	5.475	-0.015 95
60	4.216	5.355	-0.032 25
65	3.787	5.150	-0.049 25
70	3.296	4.860	-0.067 45
75	2.759	4.475	-0.087 45
80	2.197	3.980	-0.110 30
85	1.630	3.365	-0.138 05
90	1.090	2.585	-0.174 85
95	0.621	1.580	-0.234 30
100	—	0	—

leading edge radius 0.687
trailing edge radius 0.350

Fig. 3 Basic form of the blade

$$C_L = 2 \frac{S}{C} (\tan \alpha_1 - \tan \alpha_2) \cos \alpha_\infty - C_{Dp} \tan \alpha_\infty$$

2.2.4 Blade element efficiency of the cascade

The blade element efficiency of the cascade is defined as the ratio of the experimental static pressure rise to the theoretical static pressure rise, that is

$$\eta_{br} = \frac{\Delta p_r}{\Delta p_{thr}} = \frac{\Delta p_{thr} - \tilde{\omega}_p}{\frac{1}{2} \rho V_1^2 - \frac{1}{2} \rho V_2^2}$$

$$= 1 - \frac{\tilde{\omega}_p}{\frac{1}{2} \rho V_1^2 - \frac{1}{2} \rho V_2^2} = 1 - \frac{2}{\frac{C_L}{C_{Dp}} \cdot \sin 2\alpha_\infty}$$

3. Test blade and cascade

3.1 Test blade

The modified NACA 65-series compressor blade which provides slightly increased thickness distribution toward the trailing edge was used as the test blade. The basic thickness distribution and basic mean line form are given in Fig. 3. The test blade sections are shown in Fig. 4. These blades have 80 mm chord length and 180 mm span width. The center blade in the cascade has 23 static pressure taps to measure the pressure distribution on the blade surface.

3.2 Test cascade

The tests of cascade with 7 blades were run with 31 combinations of $S/C=0.7, 1.0, 1.2$ and stagger angle $\xi=45^\circ, 50^\circ, 60^\circ, 65^\circ$ to each of the

camber $C_{l_0}=0.0, 0.4, 0.8, 1.2$ in order to obtain the systematic data.

4. Description of the test equipment and measurement

The test facility used in this investigation was a low speed cascade tunnel with porous walls at the Aeronautical Research Institute, University of Tokyo. Fig. 5 shows a systematic diagram about all equipments. This facility consists of the main blower, settling duct, contracting cone, attachment of the cascade blade, low pressure-ratio exhaustor, high pressure-ratio exhaustor and measuring instrument.

Table 1 The range of incident angle

S/C	C_{l_0}	Incident angle			
		$\xi=45^\circ$	$\xi=50^\circ$	$\xi=60^\circ$	$\xi=65^\circ$
1.2	0.4		$0^\circ \sim 14^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$
	0.8		$0^\circ \sim 18^\circ$	$0^\circ \sim 12^\circ$	$0^\circ \sim 10^\circ$
	1.2		$0^\circ \sim 16^\circ$	$0^\circ \sim 12^\circ$	$0^\circ \sim 10^\circ$
1.0	0.4		$0^\circ \sim 18^\circ$	$0^\circ \sim 12^\circ$	$0^\circ \sim 10^\circ$
	0.8		$0^\circ \sim 16^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$
	1.2	$0^\circ \sim 18^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$	$0^\circ \sim 10^\circ$
0.7	0.0		$0^\circ \sim 16^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$
	0.4		$0^\circ \sim 18^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$
	0.8		$0^\circ \sim 16^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$
	1.2		$0^\circ \sim 18^\circ$	$0^\circ \sim 14^\circ$	$0^\circ \sim 10^\circ$

—unit mm—

NACA 65-(00) 10				NACA 65-(04) 10				NACA 65-(08) 10				NACA 65-(12) 10			
x_u	y_u	x_l	y_l	x_u	y_u	x_l	y_l	x_u	y_u	x_l	y_l	x_u	y_u	x_l	y_l
0.0	0.0			0.297	0.689	0.526	-0.601	0.203	0.745	0.597	-0.425	0.121	0.791	0.679	-0.311
0.4	0.618			0.485	0.849	0.715	-0.625	0.378	0.936	0.822	-0.488	0.285	1.012	0.915	-0.340
0.6	0.746			0.871	1.097	1.129	-0.755	0.749	1.243	1.251	-0.559	0.640	1.377	1.360	-0.349
1.0	0.935			1.855	1.548	2.145	-0.953	1.714	1.821	2.286	-0.631	1.584	2.081	2.416	-0.296
2.0	1.259														
4.0	1.742			3.838	2.240	4.162	-1.228	3.679	2.723	4.321	-0.701	3.529	3.193	4.471	-0.160
6.0	2.118			5.831	2.789	6.169	-1.432	5.666	3.448	6.334	-0.734	5.506	4.094	6.494	-0.024
8.0	2.432			7.830	3.253	8.170	-1.599	7.663	4.063	8.337	-0.754	7.501	4.862	8.499	0.102
12.0	2.933			11.838	4.005	12.162	-1.852	11.678	5.068	12.322	-0.761	11.521	6.124	12.479	0.337
16.0	3.314			15.854	4.583	16.146	-2.037	15.708	5.849	16.292	-0.754	15.565	7.106	16.435	0.535
20.0	3.602			19.874	5.032	20.126	-2.168	19.749	6.458	20.251	-0.730	19.623	7.879	20.377	0.713
24.0	3.808			23.897	5.362	24.103	-2.251	23.795	6.913	24.205	-0.692	23.692	8.461	24.308	0.870
28.0	3.939			27.922	5.586	28.078	-2.290	27.844	7.232	28.156	-0.640	27.768	8.876	28.232	1.012
32.0	3.997			31.948	5.710	32.052	-2.283	31.897	7.423	32.103	-0.568	31.845	9.135	32.155	1.147
36.0	3.970			35.975	5.722	36.025	-2.218	35.949	7.474	36.051	-0.466	35.924	9.226	32.076	1.286
40.0	3.850			40.000	5.614	40.000	-2.085	40.000	7.379	40.000	-0.320	40.000	9.114	40.000	1.445
44.0	3.652			44.023	5.404	43.977	-1.900	44.087	7.156	43.953	-0.148	44.000	8.907	43.930	1.605
48.0	3.373			48.044	5.086	47.956	-1.659	48.087	6.799	47.913	0.056	48.130	8.511	47.870	1.771
52.0	3.030			52.060	4.677	51.940	-1.381	52.120	6.323	51.880	0.269	52.179	7.968	51.821	1.920
56.0	2.637			56.071	4.191	55.929	-1.081	56.142	5.743	55.858	0.477	56.213	7.294	55.787	2.037
60.0	2.207			60.077	3.638	59.923	-0.774	60.154	5.066	59.846	0.662	60.231	6.491	59.769	2.101
64.0	1.758			64.078	3.029	63.922	-0.482	64.155	4.298	63.845	0.796	64.231	5.563	63.769	2.078
68.0	1.304			68.072	2.379	67.928	-0.225	68.143	3.450	67.857	0.857	68.213	4.517	67.787	1.944
72.0	0.872			72.061	1.697	71.939	-0.043	72.120	2.518	71.880	0.791	72.179	3.335	71.821	1.628
76.0	0.497			76.046	1.000	75.954	0.011	76.092	1.499	75.908	0.523	76.134	1.995	75.866	1.039
—	—			—	—	—	—	—	—	—	—	—	—	—	—

Leading edge radius=0.560

Trailing edge radius=0.280

Fig. 4 Test aerofoil

The characteristics are as follows.

Nozzle dimension : 180 mm width and 389~173 mm height (variable), inlet air velocity : 60 m/sec, the variable range of inlet air angle : $0^\circ \sim 75^\circ$, Reynolds' No. 3.2×10^5 , blade chord : 80 mm, aspect ratio : 2.25. Fig. 6 shows the attachment of the cascade. The boundary layer on the side walls was sucked through the slits before the cascade and the boundary layer on the upper and lower walls was sucked through the gaps between walls and their neighbouring blades. The porous walls were used in the side walls at the blade ends. The porous walls were made of 1 mm thick plates and had holes of 0.8 mm dia, 3 mm pitch, arranged in check pattern. Fig. 7 shows the porous walls. The suction through the slit before the cascade and the suction through the gaps between upper and lower walls and each neighbouring blades were made by the low pressure ratio exhaustor (flow rate $2 \text{ m}^3/\text{sec}$, pressure rise 1000 mmAq). The suction through the porous walls at the blade ends was made by the high pressure ratio exhaustor (flow rate $0.4 \text{ m}^3/\text{sec}$, pressure drop 400 mmHg). Inlet air state before the cascade was measured by the Prandtl-type

pitot tube and Kiel type total pressure tube. Outlet air state behind the cascade was measured by the 5-mouth arrow head type pitot tube. It traverses along the cascade approximately 10 mm downstream of the blade trailing edge. Fig. 8 shows the pitot tube and Fig. 9 shows the characteristic curve. The static pressure on the blade surface was measured at the mid-span position of the central aerofoils at each incident angle. As shown in Fig. 5 (b), each suction volume is measured by using the 10 orifices.

(a)

(b)

Fig. 5 Suction system

Fig. 6

Fig. 7

Fig. 8

Fig. 9 Characteristic curve of the pitot tube

5. Selection of the test condition

To perform the two dimensional cascade test, it is necessary to satisfy the following conditions.

(1) It is necessary to make the inlet air flow uniform along the span direction. Therefore, it is necessary to suck the air through the slit before the cascade.

(2) Each of the blades in the cascade must act on the same condition in spite of the finite number of blades. Therefore, it is necessary to suck the boundary layer through the slit on the upper and lower side walls, or the gaps between upper and lower walls and each set of neighbouring blades.

(3) It is necessary to delay the separation on the side walls at the blade ends. Therefore, it is

Fig.10 Velocity distribution with suction

necessary to suck the low energy air through the porous walls.

5.1 Control of the inlet air state before the cascade—selection of suction volume through the side wall slit before the cascade—

Fig. 10 shows velocity distributions near the walls at the stations (I), (II), (III), (IV).

t^* : boundary layer displacement thickness, mm

t_0^* : boundary layer displacement thickness for no suction, mm

h : span length, mm

$V_{\max}$: maximum air speed in the tunnel, m/sec

V : air velocity, m/sec

x : spanwise position measured from the side wall, mm

$e = \frac{2t_0^*}{h} \times 100$: the ratio of boundary layer displacement thickness for no suction to span length

G_s : suction volume

G : total flow volume through the cascade tunnel

$$g_s = \frac{G_s}{G} \times 100$$

Boundary layer thickness is defined as follows.

$$t^* = \frac{1}{V_{\max}} \int_0^{h/2} (V_{\max} - V) dx$$

Fig. 11

Fig. 12

Fig. 11 can be obtained from Fig. 10 by using t^* and g_s . In this test, t_0^* for (I) is larger than t_0^* for (II), because the side walls were set at 60° inlet angle. Therefore, (I) passage length is longer than (II) after the contracting cone. (I) and (II) show similar inclination in Fig. 12 using t^*/t_0^* and g_s . And the velocity distribution is satisfactorily uniform when suction volume ratio is 3%. Therefore, the test was carried out under that condition. Fig. 13 shows the relation between t^*/t_0^* and g_s/e_0 . When $g_s/e_0 = 1.1$, boundary layer displacement thickness for (I) and (II) is thinner than 10% of it for no suction. But, for (III) (IV), suction through the slit on the upper and lower walls does not bring any effective improvement in the velocity distribution.

Fig. 13

Fig. 14 Setting of the walls

And also the low energy flow at the corners is not removed through the slit.

5.2 Removal of the effects of the upper and lower walls

As expressed above, the boundary layer on the upper and lower wall was not so fully sucked through the slit, therefore the suction through the gaps between the upper and lower wall and each set of neighbouring blades was employed as shown in Fig. 6, and the sectional diagram is shown in Fig. 14. The

distance between wall and blade leading edge was adjusted to about 10 mm using the gauge. As we see from Fig. 10 the boundary layer thickness is thinner than 10 mm from the walls. Then if the flow volume which passes through these gaps is sucked completely, the upper and lower blade shows the same performance to the other blade, and the test cascade is considered as an infinite cascade.

5.3 Suction through the porous walls at the blade ends

NACA 65-(04) 10
S/C=1.2, $\xi=60^\circ$
(a) Characteristic curve

NACA 65-(04) 10
S/C=1.2, $\xi=60^\circ$
(b) Static pressure distribution on the blade surface

Fig. 15

When the incident angle increases, the separation on the walls arises and the flow is drifted to the mid-span. That is, the flow condition is not two-dimensional. In order to prevent it, the suction volume through the porous walls was determined to make the boundary layer sufficiently thin. And to maintain the pressure in the suction chamber sufficiently lower than the static pressure on the blade surface. V_{2a}/V_{1a} indicates the concentrated degree of flow at the mid-span. After the value of V_{2a}/V_{1a}

exceeds 1.1, it increases rapidly, and the tendencies of the outlet angle, turning angle, and total pressure loss coefficient change discontinuously.

6. Test procedure and test results

6.1 Test procedure

After the method for two-dimensional cascade test has been established, the cascade shown in Table 1 was tested with constant stagger angle.

6.2 Test results

Fig. 16

Some parts of the results are shown in Fig. 15~ Fig. 18. In these figures (a) shows the characteristics of the cascade and (b) shows the pressure distribution on the blade surface. On the characteristic curve, lateral coordinate shows the incident angle, and longitudinal coordinate shows the turning angle, outlet angle, total pressure loss coefficient, the ratio of inlet and outlet axial velocity, and $\Delta G/G$ with constant stagger, solidity and blade profile.

6.2.1 The range showing the two-dimensional

cascade performance

On the characteristic curves, the full line indicates the region of the two-dimensional performance and the dotted line indicates the region of separated state on the side wall through the cascade. It is difficult to decide the region which shows the two-dimensional performance using only $i \sim \epsilon$, and $i \sim \zeta$ curves, then, $i \sim \alpha_2$, $i \sim V_{2a}/V_{1a}$ curves and pressure distribution on the blade surface are applied to determine the region. Under these considerations.

Fig. 17

the data were divided into two groups. That is,

(1) 1st group (Fig. 15, Fig. 16)

In this group, after ζ has increased, the separation on the wall arises, then, the region of two-dimensional performance is decided definitely.

(2) 2nd group (Fig. 17, Fig. 18)

In this group, before ζ has increased, the separation on the side wall arises. It seems to fail in maintaining the two-dimensionality by sucking an insufficient volume through the porous wall, but it is evident that the two-dimensional performance is

obtained only in the full line region considering the pressure distribution on the blade surface.

6.2.2 Outlet angle

(1) When S/C , C_{l0} and ξ are constant, outlet angle has almost a constant value in the two-dimensional performance and small pressure loss.

(2) As the incident angle draws near to negative stall angle, the outlet angle decreases a little, and as the incident angle draws near to positive stall angle, the outlet angle increases a little. As the flow is drifted to the mid-span, the outlet angle decreases and

Fig. 18

has nearly the value of the two-dimensional performance.

(3) As S/C decreases or C_{i0} and ξ increase the outlet angle along the cascade becomes non-uniform outside the wake region.

6.2.3 Turning angle

(1) In the region of the two-dimensional performance, the turning angle increases continuously with the incident angle.

(2) When the incident angle increases and goes off the two-dimensional performance region, the turning angle increases discontinuously and rapidly. In this case the outlet angle decreases.

6.2.4 Total pressure loss coefficient

(1) When S/C , C_{i0} and ξ increase, total pressure loss coefficient increases.

(2) When incident angle increases and goes off the two-dimensional performance region, the total

Fig. 19 Stagger angle and outlet angle

Fig. 20 Stagger angle and outlet angle

Fig. 21 Stagger angle and outlet angle

Fig. 22

pressure loss coefficient decreases discontinuously and rapidly.

7. The discussion of the results

7.1 Design point

Design points were determined for the standard of the design procedure. The analysis of data was carried out using these points. The design points are shown in Figs. 15~18 by the arrows.

(1) In the region of the two-dimensional performance, the design incident angle is decided at the point where the total pressure loss coefficient has a minimum value. The incident angle of the design point is smaller than the incident angle of the

maximum C_L/C_{Dp} . This is to maintain the allowance of the operational range on the positive incident angle and to admit the high Mach number, considering the static pressure distribution on the blade surface.

(2) In the incident angle range of two-dimensional performance, when the maximum incident angle is the incident angle where the total pressure loss coefficient has a minimum value, the design incident angle is decided at the incident angle which shows a few degrees lower value than the incident angle where the total pressure loss coefficient has a minimum value, considering the static pressure distribution on the blade surface. These cascades

Fig. 23

Fig. 24

have a large value of ζ , and are unsuitable for design use. But these design points were selected for the standard of usage.

7.2 Stagger angle and outlet angle

The relation between the stagger angle and the outlet angle is shown in Figs. 19~21.

(1) When S/C and C_{l0} are constant, the outlet angle at the design point increases with the stagger angle linearly.

(2) $d\alpha_2/d\zeta$ increases with C_{l0} .

(3) $d\alpha_2/d\zeta$ increases with S/C .

(4) In Fig. 21 $C_{l0}=1.2$ line crosses the $C_{l0}=0.4$ line and $C_{l0}=0.8$ line. The reason is that, when α_2 increases, the total pressure loss coefficient

increases rapidly and the turning angle decreases.

7.3 The loading limit of the cascade

The loading limit is shown by the design turning angle in this paper. The analysis of data was carried out by the following procedure. That is,

(1) When S/C and C_{l0} are constant and the stagger angle is a parameter, the relations between outlet angle against turning angle, total pressure loss coefficient and incident angle are shown in Figs. 22~24. From these relations, as α_2 increases, ε and i decrease, and ζ increases for the constant S/C and C_{l0} .

(2) The relations between ε , ζ , C_L/C_{Dp} , i and C_{l0} are shown in Figs. 25~27 when α_2 and S/C

Fig. 25

Fig. 26

Fig. 27

are constant. That is,

(a) When α_2 is constant, ε has a maximum value. The C_{L0} corresponding to maximum ε is near the C_{L0} corresponding to maximum C_L/C_{Dp} . That is, when C_{L0} increases over the point corresponding to the maximum value of ε , C_L/C_{Dp} and ε decrease.

(b) When α_2 increases, the maximum values of ε and C_L/C_{Dp} decrease.

(c) Comparing Figs. 25~27 with the test results, C_{L0} corresponding to the maximum value of C_L/C_{Dp} belongs to the 1st group. The C_{L0} which belongs to the 2nd group is larger than the C_{L0} corresponding to the maximum value of ε . That is, the data showing the loading limit belong to the 1st group.

(3) The points corresponding to the maximum value of C_L/C_{Dp} are taken from Figs. 25~27. Then, where S/C is a parameter, the relations between ε , ζ , C_{L0} , C_L/C_{Dp} , and $(\tan \alpha_1 - \tan \alpha_2)$ and α_2 are shown in Fig. 28. That is, this is the loading limit.

According to the above, we understand the following.

(a) For ε

When α_2 increases, ε decreases, and when α_2 is small, ε has a small value when S/C is large. But near $\alpha_2=65^\circ$, ε has a large value when S/C is large. ε is almost constant at $\alpha_2=60^\circ$ independently of S/C . The relation is very different from the data ever published.

(b) For ζ

When α_2 increases or S/C decreases, ζ increases. Especially ζ increases extremely for $S/C=0.7$ and $\alpha_2>60^\circ$.

Fig. 28

(c) For C_L/C_{Dp}

When α_2 increases or S/C decreases, C_L/C_{Dp} decreases. Especially C_L/C_{Dp} decreases extremely for $S/C=0.7$ and $\alpha_2>60^\circ$.

(d) For C_{L0}

Fig. 28 shows the relation of design α_2 against optimum C_{L0} .

(e) For $(\tan \alpha_1 - \tan \alpha_2)$

When S/C is large, $(\tan \alpha_1 - \tan \alpha_2)$ increases

with α_2 . But $(\tan \alpha_1 - \tan \alpha_2)$ decreases with α_2 for $S/C \approx 0.7$.

8. Conclusion

Results obtained are as follows.

(1) The cascade performance was obtained for $S/C=0.7 \sim 1.2$, $C_{l0}=0.0 \sim 1.2$ and $\xi=45^\circ \sim 65^\circ$, and the design points were decided.

(2) From these data, the relation between stagger angle and outlet angle was decided.

(3) Analysing these data, design loading limit was decided for outlet angle, and also total pressure loss coefficient, camber, lift-drag ratio, and $(\tan \alpha_1 - \tan \alpha_2)$ were deduced.

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