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NOISE REDUCTION BY MEANS OF VARIABLE-GEOMETRY INLET GUIDE VANES IN A CASCADE APPARATUS

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16. Abstract

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SUMMARY

Noise-reduction studies involving variable-geometry inlet guide vanes for choking have been made by using a two-sector cascade apparatus with three different inlet configurations: a rotating offset inlet guide vane (IGV), a translating wave IGV, and a stationary uncambered IGV. All three configurations were operated in both the choked and unchoked modes for a range of airflows.

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INTRODUCTION

It has been established that pure tones radiating from an axial-flow compressor can be reduced by choking in the inlet, that is, formation of a sonic barrier, as described in references 1 and 2. Two difficulties have been encountered in attempting to use this phenomenon for noise attenuation. The first has been failure to obtain large noise reductions because of the inability to get a continuous shock wave across a relatively large area (ref. 1). The other difficulty is large diffusion losses, and hence lower pressure recoveries, because of the high diffusion angles necessary as a result of axial space limitations (ref. 2). Choking in the inlet guide vanes offers relief from both of these difficulties because each area to be choked is relatively small and because of the inherently low diffusion angles on the vanes. The first inlet-guide-vane choking information became available with the publication of references 3 and 4. Reference 3 demonstrated the feasibility of inlet-guide-vane choking, and reference 4 demonstrated that choking could be made to occur throughout the operating range of the compressor by installing different sets of thicker inlet guide vanes. Reference 5 further demonstrated that a sonic inlet could be made variable and made to function on a gas-turbine engine.

This study examined mechanically simple devices for choking anywhere within the operating range while the compressor (or engine) was operating. Three inlet choking mechanisms were selected for their simplicity and tested in a laboratory cascade apparatus. The cascade apparatus was used to provide an inexpensive and quick evaluation of the potential of these mechanisms prior to any testing with a compressor. The main purpose of this evaluation was to determine which of these three mechanisms was most promising both acoustically and aerodynamically. The cascade apparatus simulated a two-dimensional two-sector section of the compressor used in the tests of references 3 and 4. Aerodynamic and acoustic results of these tests, which were reported preliminarily in reference 6, are presented in this report.

SYMBOLS

A_1	cross-sectional area at pitot-tube location
A_2	cross-sectional area at throat section
A_*	cross-sectional area required for choking
M_t	axial Mach number of one-dimensional flow in throat area formed by adjacent inlet guide vanes
$\Delta y'$	distance between adjacent inlet guide vanes
x'	axial position of translating wave IGV
θ	inlet-guide-vane setting angle, degrees

Abbreviations:

IGV	inlet guide vane
SPL	sound pressure level, dB (re 0.0002 microbars)

APPARATUS AND PROCEDURES

Description of Equipment

Cascade apparatus.- A two-sector cascade apparatus was designed for this study. The apparatus and associated instrumentation are shown in the photograph of figure 1 and schematically in figure 2. The inlet to the cascade apparatus was designed to operate slightly below atmospheric pressure and at airflows from 0.454 to 0.781 kg/sec (1.0 to 1.5 lbm/sec). The average pressure recovery for the apparatus, without a test section installed, was found to vary from 0.97 to 0.99, depending on the airflow.

The three inlet configurations tested are shown in the photographs of figure 3 and are shown schematically in figure 4. Coordinates of the configurations are given in tables I, II, and III.

Rotating offset IGV.- The rotating offset IGV is shown in figures 3(a) and 4(a). The object of this geometry was to obtain maximum displacement at the leading and trailing edges, as compared with an uncambered IGV; hence, large area reductions are obtained with a minimum of IGV rotation. This minimum rotation would retard the onset of flow separation from the rotated IGV by minimizing the deviation of the IGV surfaces from the streamline. This configuration creates two throats, one at the leading edge and the other at the trailing edge. With this configuration, only every other IGV would be rotated.

Translating wave IGV.- The translating wave IGV is shown in figures 3(b) and 4(b), and the object of this geometry was to allow for the required area reduction for choking by translating every other IGV, while keeping the IGV shape such that the deviation of its surface from the streamline is minimized. This shape was intended to minimize the flow separation and hence maximize the pressure recovery of the device.

Stationary uncambered IGV.- The stationary uncambered IGV is shown in figures 3(c) and 4(c). The object of this geometry was to attain choked flow by increasing the airflow while minimizing inlet losses by maintaining constant IGV geometry which was near an absolute minimum deviation of its surface from the streamline. The data collected for this device would also be applied to an inlet configuration which would cause the cross-sectional area to be reduced by insertion of additional uncambered IGV when choking is required. The major difference between this device and the other two is that this device would require the insertion of at least several additional uncambered IGV to accomplish the area reduction needed for choking.

Instrumentation

Two 12.7-mm-diameter (0.5 in.) condenser microphones were used to measure the noise generated by the noise source and the noise upstream of the test configurations. Output signals were recorded on a graphic level recorder after passing through a

1/3-octave analyzer. The overall frequency response of the recording system was flat within ±2 dB from 100 Hz to 20 000 Hz. The microphones were located as shown in figure 2 and were flush mounted in the walls. The problems of amplitude variations due to standing wave shifts and reflection complications were minimized by locating the reference microphone as close as possible to the noise source. Experience gained during the investigation indicated that this noise level was sufficiently accurate because it remained relatively constant throughout a particular test. The microphone located upstream of the test configuration is known to be influenced somewhat by reflections from the inlet and the downstream hard surface. This arrangement was a reasonable compromise considering the alternatives and the objectives of this investigation.

Procedure and Measurements

To begin the experiment, the noise source was activated and regulated. The noise-source frequency was set at approximately 500 Hz which was at the resonance of the test channel. It was necessary to operate at this frequency to have a sufficient noise-source amplitude above the broadband noise of the airflow. This procedure resulted in a signal-to-background noise ratio of approximately 50 dB. At this time the flow control valve was opened to obtain the required airflow for the particular test. After the temperature and pressure stabilized, acoustic and aerodynamic data were obtained during a 5- to 10-minute period. During this time, total-pressure probes were used to survey the cross section to obtain total-pressure profiles. These profiles were obtained by traversing the cross section vertically and then horizontally at two downstream stations. The maximum total pressures were obtained by omitting the total-pressure reading very close to the wall in order to more closely simulate a compressor. The temperature and pressure probes were located as shown in the sketch (fig. 2).

RESULTS AND DISCUSSION

The primary variables for the rotating offset IGV and the translating wave IGV were cross-sectional-area reduction and air velocity. The offset IGV configuration was used to study the acoustic and aerodynamic performances of a simple, lightweight, choking mechanism. The wave IGV configuration was used to study a slightly more complex device which promised better aerodynamic performance than the offset IGV configuration because of improved geometry in the choked mode. The uncambered IGV configuration was used to study a device which promised much improved aerodynamic performance over the offset IGV and the wave IGV configurations because of further improved geometry in the choked mode. The primary variable for the uncambered IGV configuration was airflow.

Noise Spectra

Rotating offset IGV.- The effects of rotating an IGV to choke an inlet were studied to evaluate the rotating offset IGV for use in an axial-flow-compressor inlet and to compare it with other such devices. Noise measurements were obtained with the offset IGV configuration for a range of angles of rotation and airflows. Typical noise spectra are shown in figure 5(a). The dashed curve represents the 1/3-octave spectrum of the noise in the inlet when the offset IGV is set at $\theta = 20^{\circ}$ – that is, with an area reduction of 57.3 percent – and the flow is choked. The presence of harmonics of the fundamental tone of the air modulator noise source is due to nonlinearity effects in the air modulator. The noise reductions of the first, second, and third harmonics of the frequency generated are approximately 21 dB, 14 dB, and 6 dB, respectively. Noise reductions of the broadband noise across the entire spectrum are caused partly by choking and partly by the reduced airflow. This type of spectrum alteration is characteristic of choked flow as shown in figure 5 of reference 1. However, the magnitude of the noise reduction for the offset IGV configuration was less than those obtained in reference 1. The noise spectrum of the offset IGV configuration (fig. 5(a)) in the choked mode shows that the fundamental frequency is still present which indicates that the two throats are not fully choked acoustically, although they were observed to be choked aerodynamically since further opening of the control valve was ineffective. This could be due to noise propagation through the boundary layer in the area of separated flow believed to be present when the IGV is rotated.

Translating wave IGV.- The effects of translating an IGV to choke an inlet were also studied to evaluate the translating wave IGV for use in an axial-flow-compressor inlet and to compare it with other such devices. Noise measurements were obtained with the wave IGV configuration for a range of translated positions and airflows. Typical noise spectra are shown in figure 5(b). The solid-line curve represents the 1/3-octave spectrum of the noise in the inlet when the wave IGV is in the unchoked position, that is, with a 7-percent area reduction, and the flow is not choked. The dashed curve represents the 1/3-octave spectrum of the noise in the inlet when the wave IGV is in the choked position, that is, with an area reduction of 51.5 percent, and the flow is choked. The noise reductions of the first, second, and third harmonics of the frequency generated are approximately 34 dB, 30 dB, and 23 dB, respectively. Noise reductions of the broadband noise across the entire spectrum are caused partly by choking and partly by the reduced airflow. Further inspection of the noise spectrum (fig. 5(b)) in the choked mode shows that the fundamental frequency is still present which indicates that the two throats are not fully choked acoustically although they were observed to be choked aerodynamically. In spite of this fact, it can be seen that the wave IGV configuration yields similar noise reduction results when compared with other choking devices. (See refs. 1 and 2.)

Stationary uncambered IGV.- The effects of using uncambered airfoils to reduce the cross-sectional area of an inlet were also studied to evaluate the stationary uncambered IGV for use in an axial-flow-compressor inlet and to compare it with other such devices. Noise measurements were obtained with the stationary uncambered IGV configuration for a series of airflows, including and exceeding the airflows measured in the two preceding test configurations.

Typical noise spectra are shown in figure 5(c). The solid curve represents the 1/3-octave spectrum of the noise in the inlet when the uncambered IGV is without airflow. The dashed curve represents the 1/3-octave spectrum of the noise in the inlet when the uncambered IGV is fully choked aerodynamically and acoustically. The noise reductions of the first, second, and third harmonics of the frequency generated are approximately 49 dB, 29 dB, and 24 dB, respectively. Noise reductions of the broadband noise across the entire spectrum are caused entirely by acoustic choking since the airflow was increased from the unchoked to the choked mode. Further inspection of the noise spectrum (fig. 5(c)) in the choked mode shows that the fundamental frequency is no longer present which indicates that the throat is fully choked acoustically. The uncambered IGV configuration yields more significant noise reduction than the offset IGV configuration and the wave IGV configuration studied in this investigation, as well as the other devices of references 1 and 2.

Noise Reduction

A series of experimental noise spectra of the type shown in figure 5 was obtained, and the peak values of the fundamental frequency were noted. The unchoked mode for all configurations was taken to be the reference 0 dB. The differences in SPL between the reference and the subsequent test conditions were plotted as fundamental frequency noise reduction as a function of center-line Mach number in figure 6. The center-line Mach number was obtained by finding first the axial Mach number in a section of the cascade apparatus ahead of the test section by use of a pitot tube. Next, by using a standard table (ref. 7) for compressible subsonic flow, the ratio A_1/A_* that corresponds to this axial Mach number was noted. Multiplying this ratio by the ratio A_2/A_1 yielded another ratio A_2/A_* which applies to the condition in the throat of the choking device. The value of A_2/A_* corresponds to the Mach number in the same compressible flow table. This Mach number value has been termed center-line Mach number for the purposes of this report.

Rotating offset IGV.- The triangular symbols in figure 6 refer to the rotating offset IGV configuration. As the two throat areas are reduced by rotating the center IGV, the center-line throat Mach number is increased. There is a sharp decline in the noise level up to a center-line throat Mach number of about 0.5. Beyond this value the noise reduction is very gradual as the Mach number is further increased to 1.0 by reducing the throat areas to approximately 50 percent of the open area. The maximum noise reduction obtained with this configuration was 21 dB.

Translating wave IGV.- The circular symbols in figure 6 refer to the translating wave IGV configuration. As the two throat areas are reduced by translating the center IGV, the center-line throat Mach number is increased. There is a sharp decline in noise level up to a center-line Mach number of about 0.5. Beyond this value the noise reduction is gradual as the Mach number is further increased to 1.0 by reducing the throat areas to approximately 50 percent of the open area. The maximum noise reduction obtained with this configuration was 34 dB.

Stationary uncambered IGV.- The square symbols in figure 6 refer to the stationary uncambered IGV configuration. The center-line throat Mach number is increased by further opening of the flow control valve. There is a gradual decrease in noise level up to a center-line throat Mach number of about 0.85. Above this value the noise reduction becomes much larger as the Mach number is further increased to a maximum of 1.0. The maximum noise reduction obtained with this configuration was 49 dB. The difference in the shape of this curve and the shape of a similar curve in reference 1 is believed to be due to the generation of higher noise levels by the compressor at the higher center-line throat Mach numbers. In addition, reference 1 uses average axial Mach number for one-dimensional flow instead of the approximation of center-line throat Mach number used in figure 6. There is also the possibility that the difference may be partially due to frequency effects. The curve in reference 1 was for a series of high frequencies, from 7000 Hz to 10 000 Hz, whereas this study involved only a single low frequency, 500 Hz.

Total-Pressure Recovery

Values of maximum total-pressure recovery were obtained which corresponded to the noise reduction data presented in the previous figure (fig. 6). Maximum total-pressure recovery as a function of center-line throat Mach number for the three configurations is shown in figure 7. The symbol representation is the same as in the previous figure. Of the three configurations tested, the uncambered IGV configuration was the best as far as total-pressure recovery was concerned. Even during choked-mode operation, the total-pressure recovery for the uncambered IGV configuration was no lower than 0.94. This value is higher than any previously measured. (See refs. 1 and 2.) The values of total-pressure recovery for the offset and wave configurations were reasonably high (0.93 and 0.96, respectively) at the lower Mach numbers but became increasingly lower at the higher Mach numbers (0.57 and 0.66, respectively). From these results, it appears that much more attention needs to be given to the obvious problem of minimizing flow separation from the unusual shapes of both the offset IGV and wave IGV configurations. Figures 8 and 9 show the results of typical total-pressure profiles obtained from these tests.

Referring to figure 8, the maximum average total-pressure recovery in the horizontal plane is approximately 0.965 for the 0.25-chord location and approximately 0.960 for the 1.25-chord location. The two patterns are not quite symmetrical which is believed to be due to a small discontinuity in the surface between 0.25 chord and 1.25 chords as indicated by the left side of figure 8. This discontinuity may also account for the dip in the 1.25-chord curve. The shape of the curves on the right side gives an indication of the boundary-layer thicknesses. Referring to figure 9, the maximum total-pressure recovery in the vertical plane is approximately 0.965 for the 0.25-chord location and approximately 0.960 for the 1.25-chord location. Although these maximum values are nearly the same for figures 8 and 9, the shape of the curves are quite different because of the total-pressure probe passing through the wake of the IGV when traversing vertically. A decrease in the pressure defect is observed as the probe is moved farther downstream from the IGV.

CONCLUDING REMARKS

Noise reduction studies involving variable-geometry inlet guide vanes for choking have been made by using a two-sector cascade apparatus with three different inlet configurations: a rotating offset IGV, a translating wave IGV, and a stationary uncambered IGV. All three configurations were operated in both the choked and unchoked modes for a range of airflows.

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Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., October 5, 1971.

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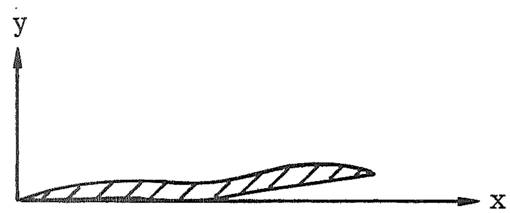
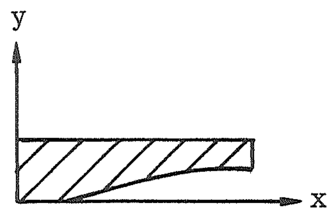
TABLE I.- COORDINATES FOR ROTATING OFFSET IGV

(a) Vane



x		y_{lower}		y_{upper}	
mm	in.	mm	in.	mm	in.
0	0	0	0	0.51	0.02
2.5	.10	0	0	.76	.03
5.1	.20	0	0	1.27	.05
7.6	.30	0	0	1.52	.06
10.2	.40	0	0	1.78	.07
12.7	.50	0	0	1.78	.07
15.2	.60	0	0	1.78	.07
17.8	.70	0	0	1.78	.07
20.3	.80	0	0	1.78	.07
22.9	.90	0	0	1.78	.07
25.4	1.00	0	0	1.78	.07
28.0	1.10	0	0	1.78	.07
30.5	1.20	0	0	1.78	.07
33.0	1.30	0	0	1.78	.07
35.6	1.40	0	0	1.78	.07
38.1	1.50	0	0	1.78	.07
40.6	1.60	0	0	1.78	.07
43.2	1.70	0	0	1.78	.07
45.7	1.80	.25	.01	2.03	.08
48.3	1.90	.51	.02	2.29	.09
50.8	2.00	.51	.02	2.29	.09
53.3	2.10	.76	.03	2.54	.10
55.9	2.20	1.02	.04	2.54	.10
58.4	2.30	1.52	.06	2.54	.10
61.0	2.40	2.03	.08	2.54	.10
63.5	2.50	0	0	2.54	.10

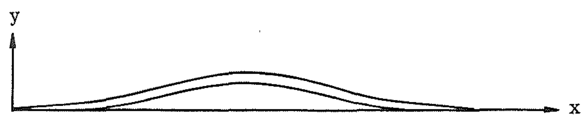
(b) Walls adjacent to IGV



x		y	
mm	in.	mm	in.
0	0	0	0
6.4	.25	.25	.01
12.7	.50	.76	.03
19.1	.75	1.52	.06
25.4	1.00	2.54	.10
31.8	1.25	3.30	.13
38.1	1.50	4.06	.16
44.5	1.75	4.57	.18
50.8	2.00	4.57	.18
57.2	2.25	4.57	.18
63.5	2.50	4.57	.18

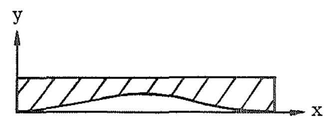
TABLE II.- COORDINATES FOR TRANSLATING WAVE IGV

(a) Vane



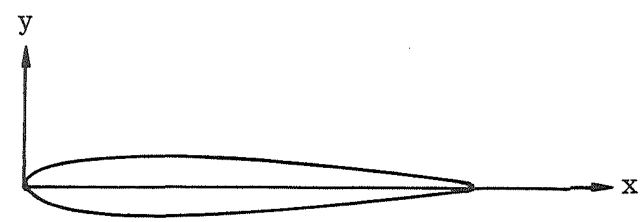
x		y_{lower}		y_{upper}	
mm	in.	mm	in.	mm	in.
0	0	0	0	0	0
6.4	.25	0	0	.51	.02
12.7	.50	0	0	1.02	.04
19.1	.75	0	0	1.27	.05
25.4	1.00	0	0	1.52	.06
31.8	1.25	.76	.03	1.78	.07
38.1	1.50	1.52	.06	2.03	.08
44.5	1.75	2.29	.09	2.54	.10
50.8	2.00	3.05	.12	3.56	.14
57.2	2.25	4.32	.17	5.08	.20
63.5	2.50	5.08	.20	5.59	.22
69.9	2.75	6.35	.25	7.11	.28
76.2	3.00	7.11	.28	8.13	.32
82.6	3.25	7.37	.29	8.64	.34
88.9	3.50	7.37	.29	8.89	.35
95.3	3.75	7.37	.29	8.64	.34
101.6	4.00	7.11	.28	8.13	.32
108.0	4.25	6.35	.25	7.11	.28
114.3	4.50	5.08	.20	5.59	.22
120.7	4.75	4.32	.17	5.08	.20
127.0	5.00	3.05	.12	3.56	.14
133.4	5.25	2.29	.09	2.54	.10
139.7	5.50	1.52	.06	2.03	.08
146.1	5.75	.76	.03	1.78	.07
152.4	6.00	0	0	1.52	.06
158.8	6.25	0	0	1.27	.05
165.1	6.50	0	0	1.02	.04
171.5	6.75	0	0	.51	.02
177.8	7.00	0	0	0	0

(b) Walls adjacent to IGV

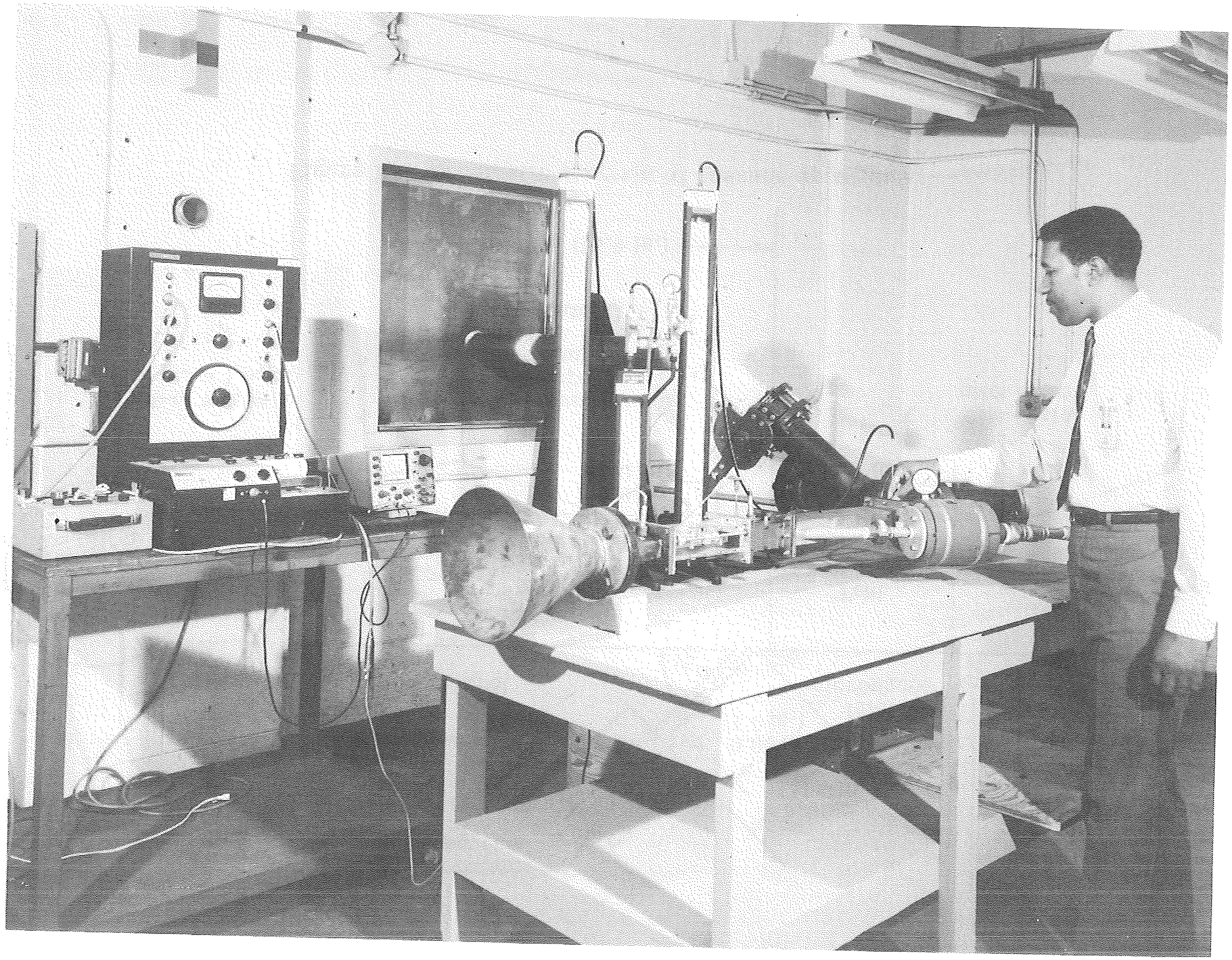


x		y	
mm	in.	mm	in.
0	0	0	0
6.4	.25	0	0
12.7	.50	0	0
19.1	.75	0	0
25.4	1.00	0	0
31.8	1.25	.25	.01
38.1	1.50	1.02	.04
44.5	1.75	2.03	.08
50.8	2.00	3.30	.13
57.2	2.25	4.57	.18
63.5	2.50	6.10	.24
69.9	2.75	7.11	.28
76.2	3.00	8.13	.32
82.6	3.25	8.38	.33
88.9	3.50	8.64	.34
95.3	3.75	8.38	.33
101.6	4.00	8.13	.32
108.0	4.25	7.11	.28
114.3	4.50	6.10	.24
120.7	4.75	4.57	.18
127.0	5.00	3.30	.13
133.4	5.25	2.03	.08
139.7	5.50	1.02	.04
146.1	5.75	.25	.01
152.4	6.00	0	0
158.8	6.25	0	0
165.1	6.50	0	0
171.5	6.75	0	0
177.8	7.00	0	0

TABLE III.- COORDINATES FOR STATIONARY UNCAMBERED IGV



x		y	
mm	in.	mm	in.
1.3	0.050	0.79	0.031
2.5	.100	1.07	.042
5.1	.200	1.47	.058
10.2	.400	2.03	.080
15.2	.599	2.41	.095
20.3	.799	2.69	.106
25.4	.998	2.87	.113
30.4	1.198	3.00	.118
35.5	1.398	3.05	.120
40.6	1.597	3.00	.118
45.6	1.797	2.92	.115
50.7	1.997	2.77	.109
55.8	2.196	2.54	.100
60.9	2.396	2.34	.092
65.9	2.596	2.11	.083
71.1	2.795	1.91	.075
76.1	2.995	1.68	.066
81.2	3.195	1.45	.057
86.2	3.394	1.24	.049
91.3	3.593	1.02	.040
96.4	3.794	.81	.032
101.4	3.993	0	0



L-70-6739

Figure 1.- Test apparatus.

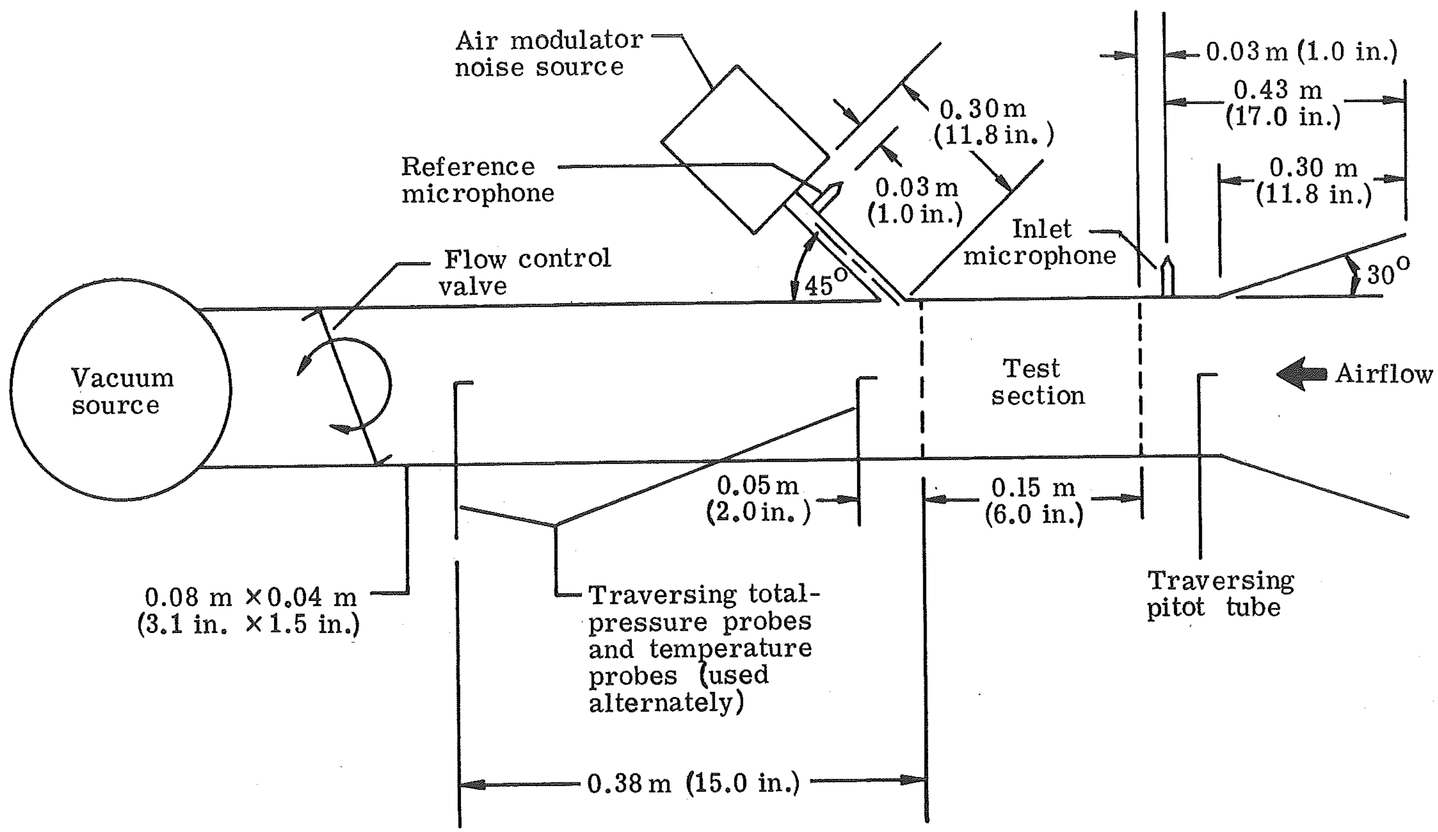
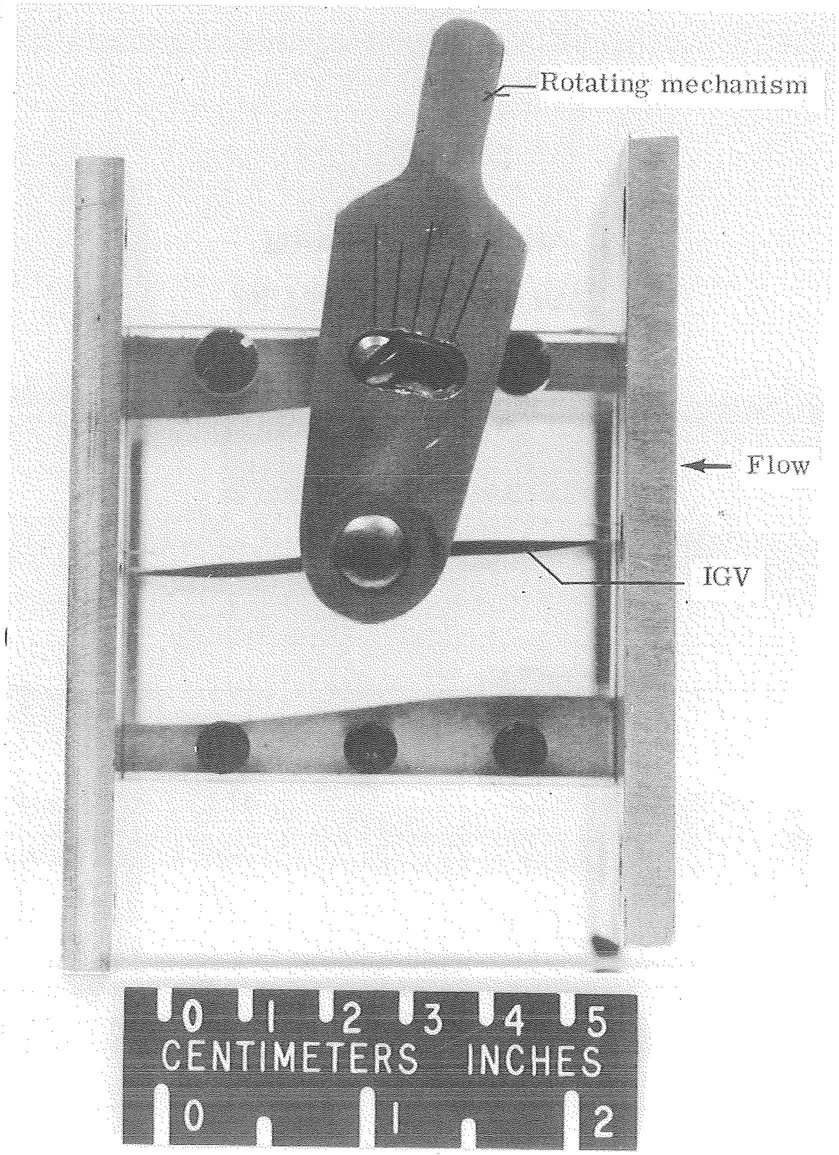


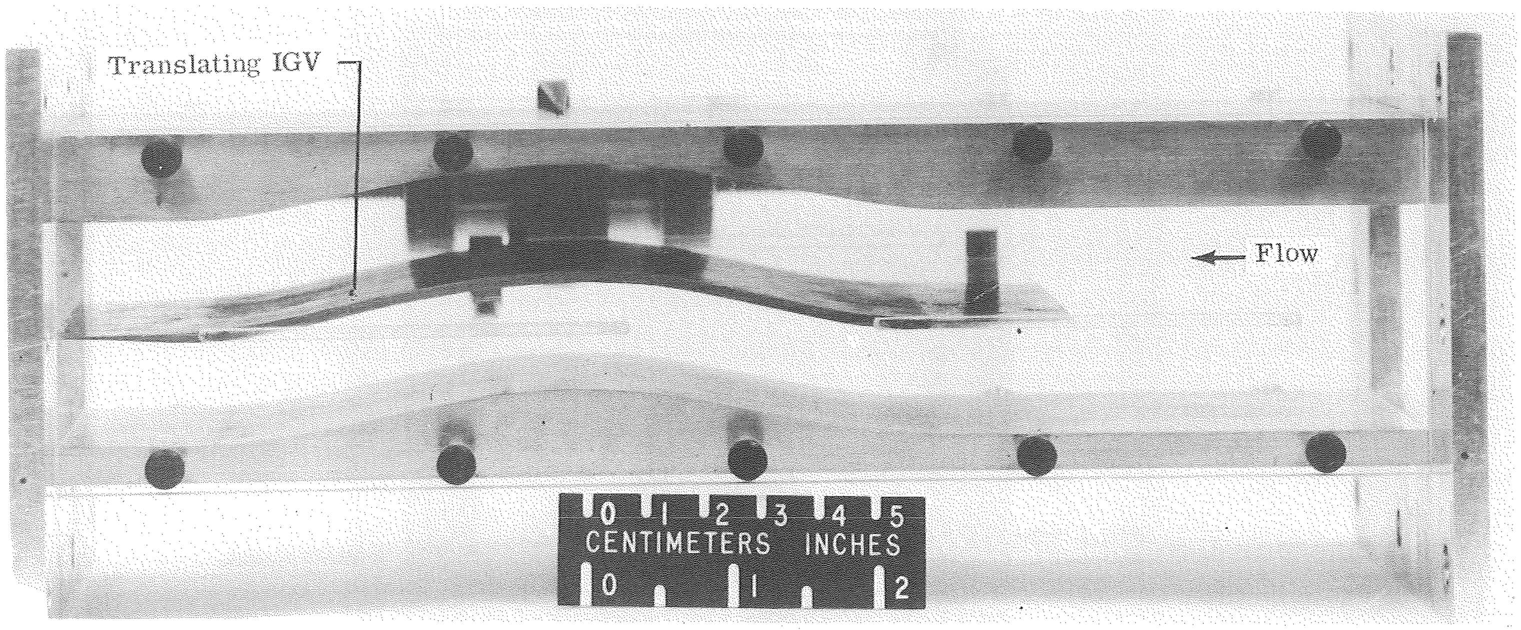
Figure 2.- Schematic diagram of cascade apparatus.



L-71-2413.1

(a) Rotating offset IGV.

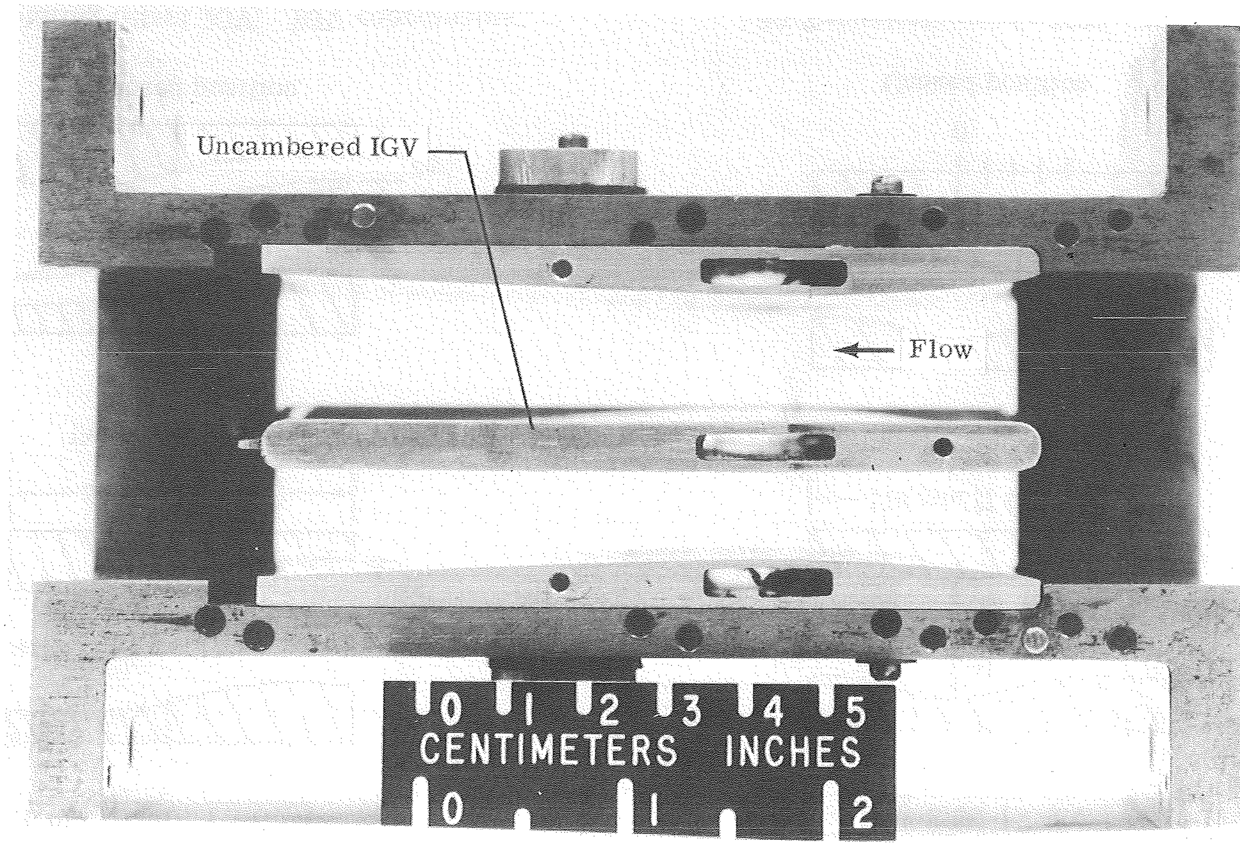
Figure 3.- Photographs of inlet configurations.



L-71-2409.1

(b) Translating wave IGV.

Figure 3.- Continued.

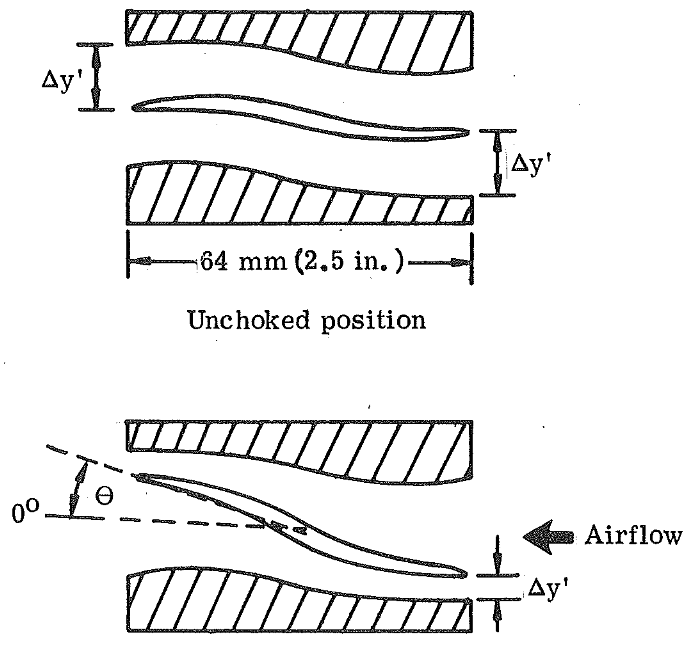


L-71-2412.1

(c) Stationary uncambered IGV.

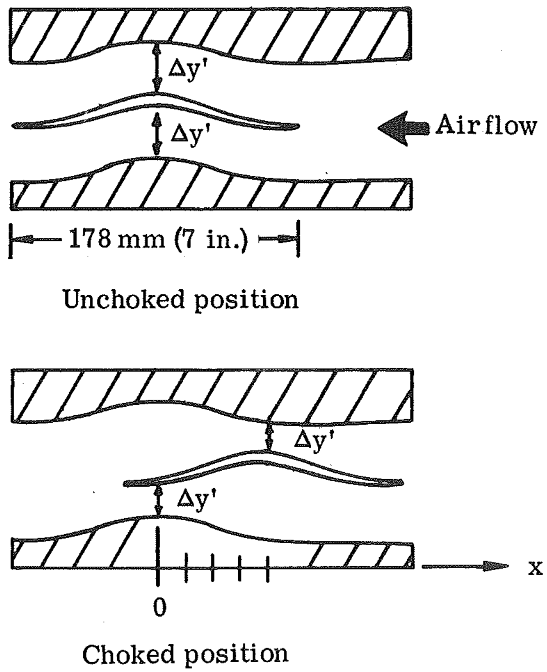
Figure 3.- Concluded.

Θ, deg	$\Delta y'$	
	mm	in.
0	19.1	0.75
5	16.3	0.64
10	13.0	0.51
15	10.4	0.41
20	8.1	0.32



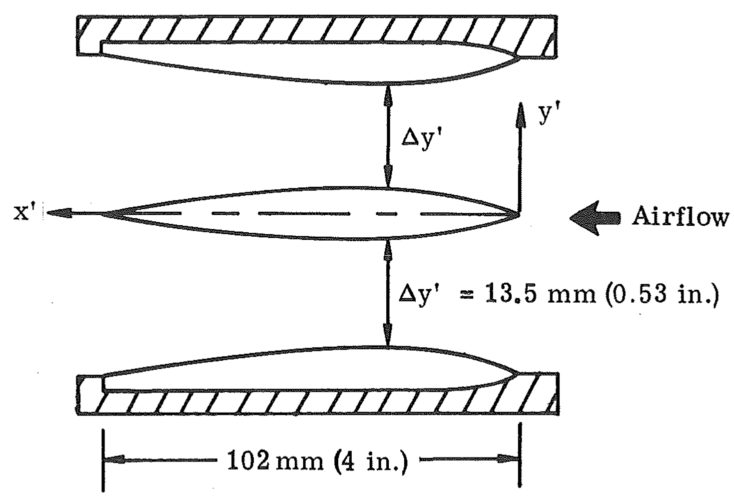
(a) Rotating offset IGV. IGV coordinates given in table I.

x'		$\Delta y'$	
mm	in.	mm	in.
0	0	18.0	0.71
16.3	0.64	15.2	0.60
32.5	1.28	12.2	0.48
48.8	1.92	10.2	0.40
65.0	2.56	9.4	0.37



(b) Translating wave IGV. IGV coordinates given in table II.

Figure 4.- Schematic diagrams of inlet configurations.



(c) Stationary uncambered IGV. IGV coordinates given in table III; IGV's have thickness-chord ratios of 0.06.

Figure 4.- Concluded.

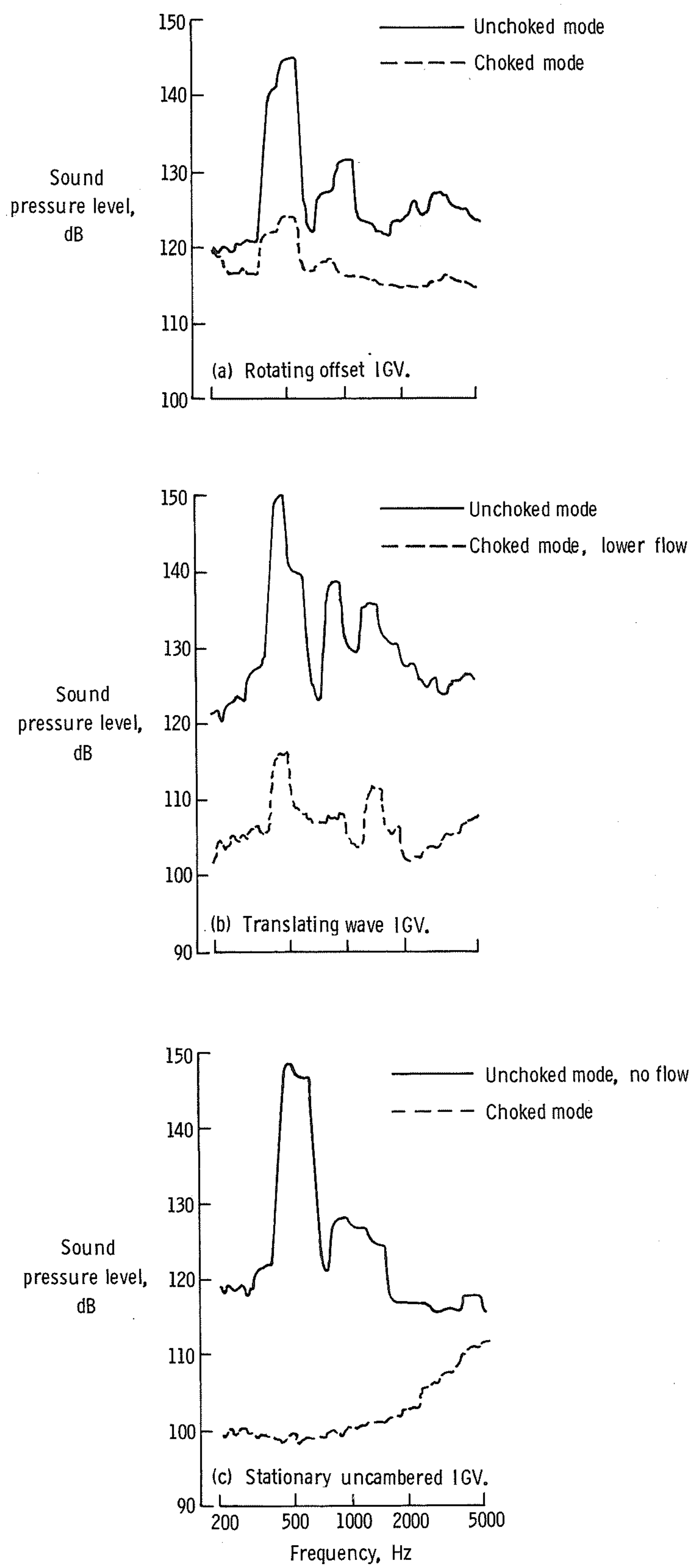


Figure 5.- Noise spectra of variable-geometry inlet guide vanes.

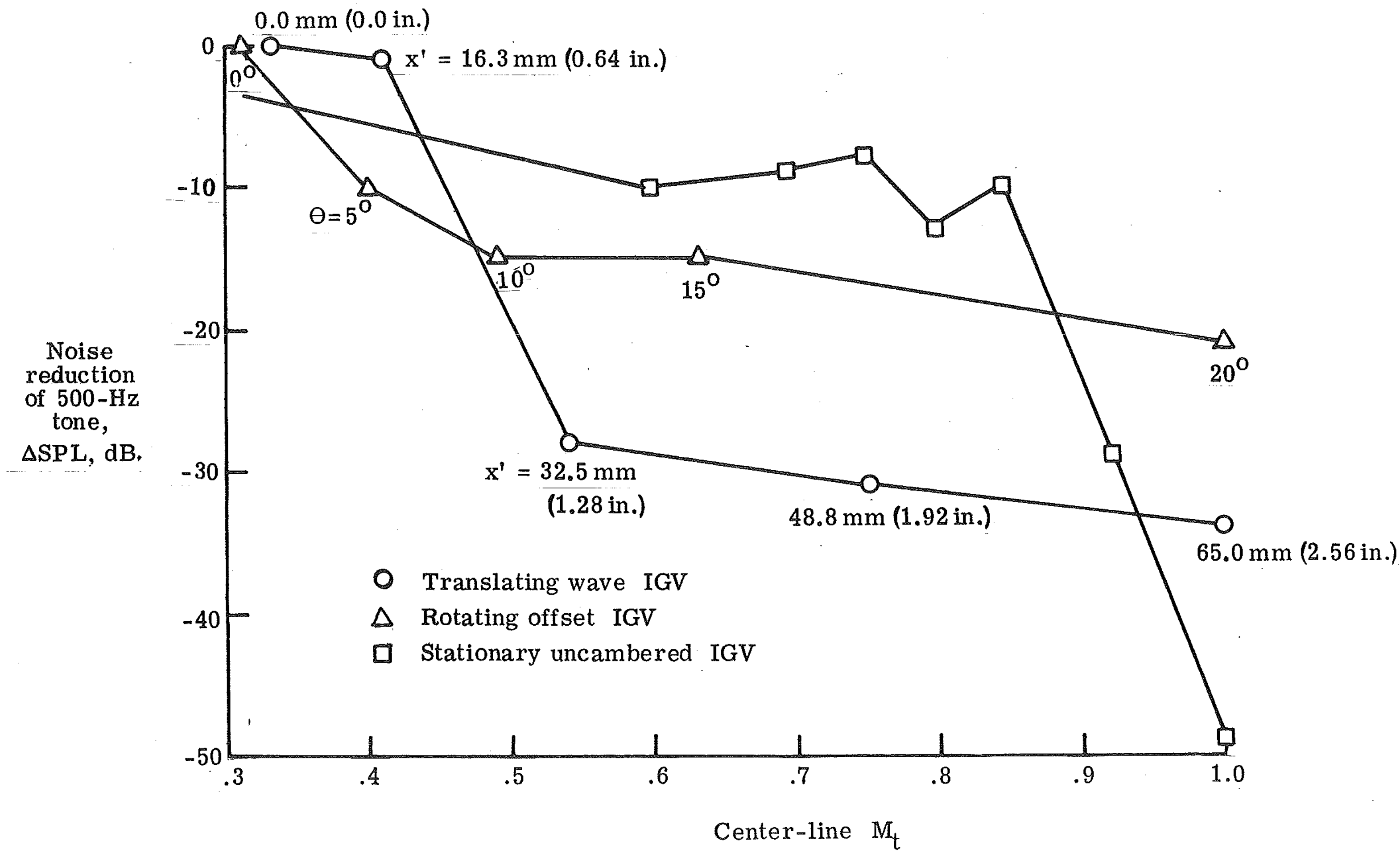


Figure 6.- Effect of estimated center-line Mach number on sound pressure level of 500-Hz tone.

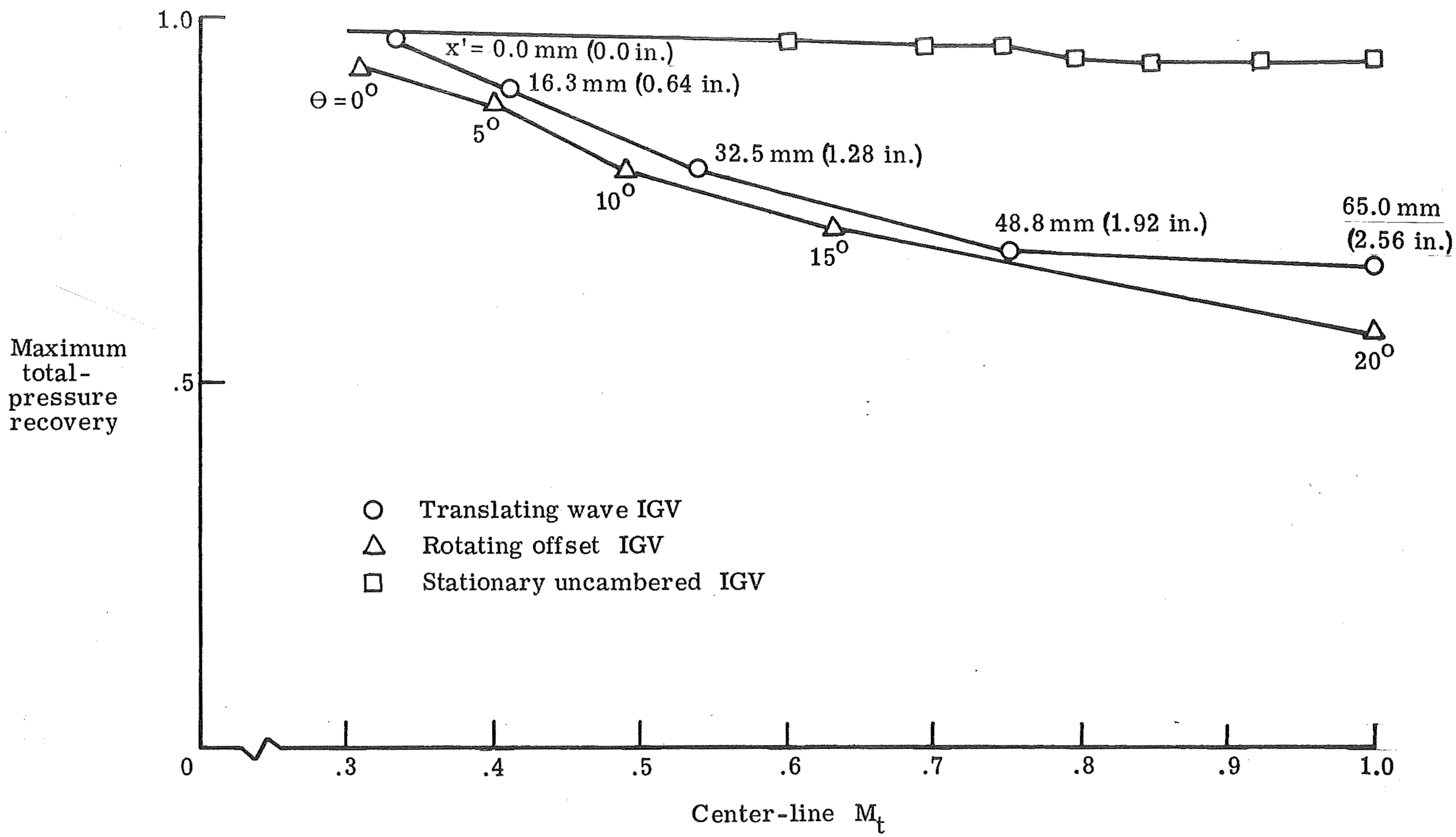


Figure 7.- Effect of estimated center-line Mach number on total pressure recovery.

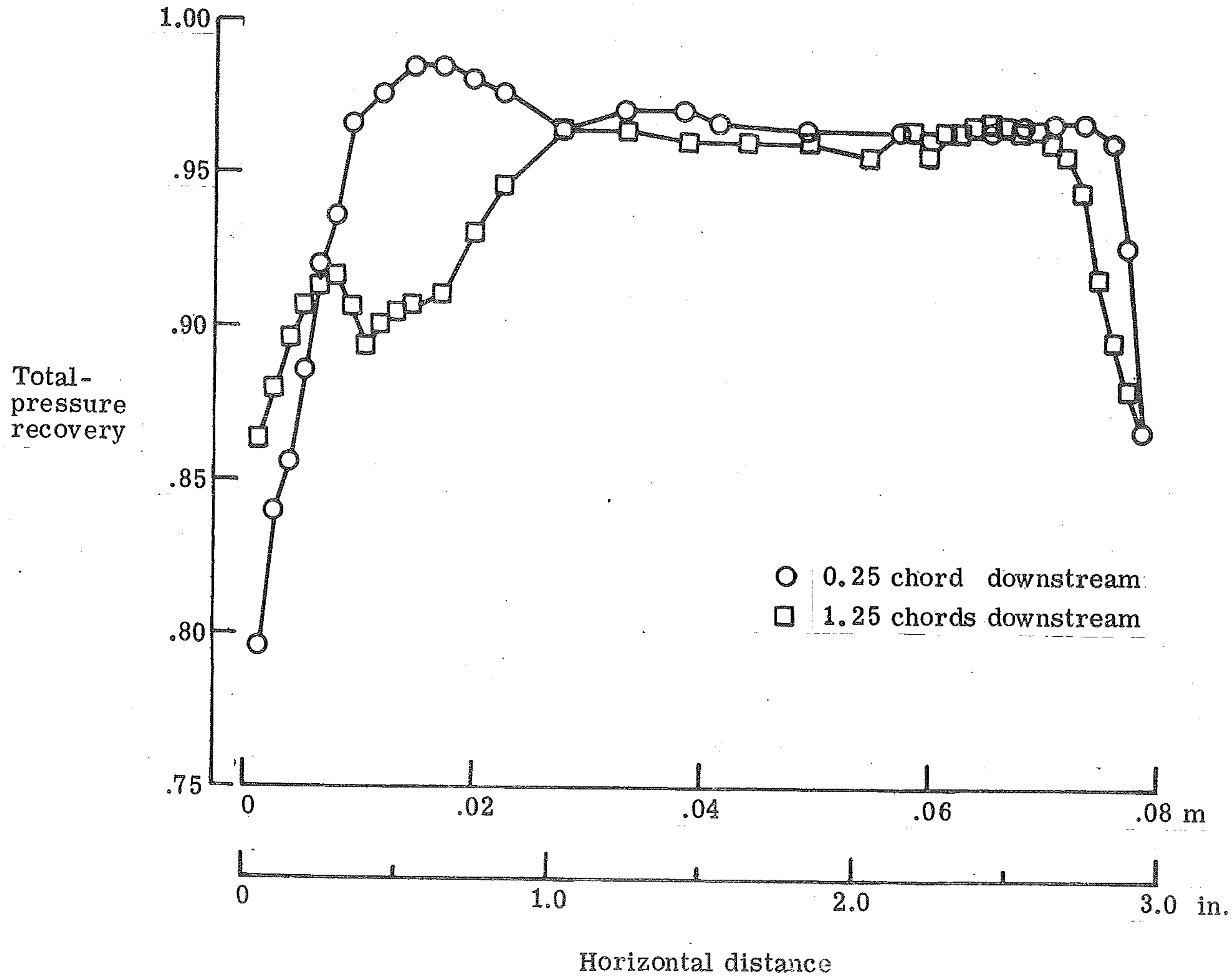


Figure 8.- Profile of total pressure in the horizontal plane.

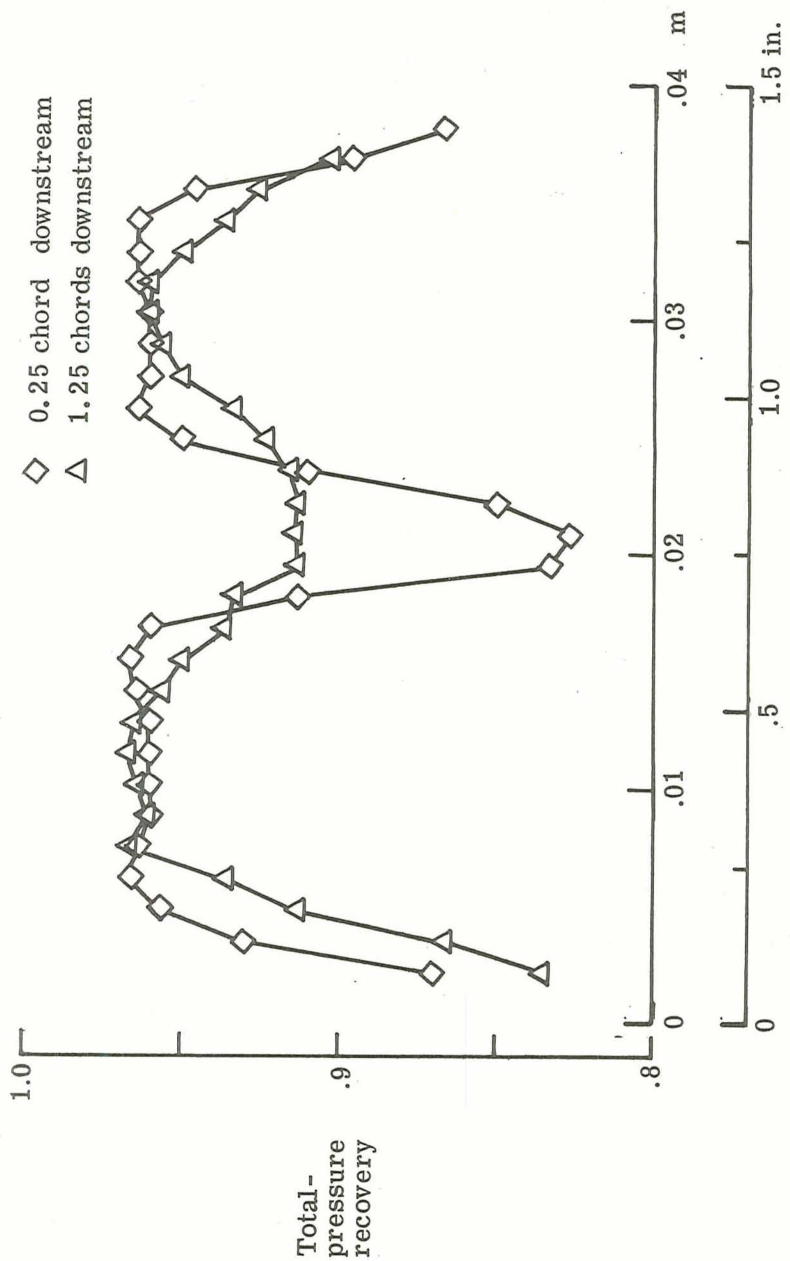


Figure 9.- Profile of total pressure in the vertical plane.

NASA-Langley, 1971 —— 2 L-7852

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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