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NOISE REDUCTION BY MEANS OF INLET-GUIDE-VANE CHOKING IN AN AXIAL-FLOW COMPRESSOR

by David Chestnutt

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SUMMARY

Studies have been made to evaluate noise-reduction benefits obtainable by alteration of the inlet guide vanes of a specially designed 25-pound/second (11.32-kilogram/second) three-stage transonic axial-flow research air compressor. Particular attention has been given to the use of inlet guide vanes to choke the flow aerodynamically for the purpose of preventing noise radiation out of the inlet. Choking was obtained in the inlet guide vanes either by increasing the thickness of each inlet guide vane or by turning the inlet guide vanes to reduce the air passage area and increase the airflow. When the vane thickness was increased, there were no compressor-efficiency losses. When the vanes were turned, there was an average compressor-efficiency loss of 8 percent. The results indicate that inlet guide vanes with variable thickness hold the most promise for maximum noise reductions without compromising compressor performance. However, for both methods of obtaining choked flow, there were pressure-ratio losses of 7 to 8 percent. The corresponding noise reductions obtained in both choked-flow modes were 25 to 30 decibels in the overall sound pressure level and 36 decibels in the first-rotor-blade-passage-frequency sound pressure level.

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. Difficulties previously encountered have been either failure to obtain large noise reductions because of the inability to get a continuous shock wave across a relatively large area (ref. 1) or, once having obtained this condition, suffering large diffusion losses 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 in that each area to be choked is relatively small and because of the inherently low diffusion angles on the vanes.

One of the most important considerations when reducing fan or compressor noise is to determine accurately the performance losses. These losses have been carefully documented for the tests presented in this report. It is a purpose of this report to show that the production of many shock waves in the inlet guide vanes substantially reduces the noise radiated without causing large performance losses. In order to accomplish this, systematic tests have been performed for two thicknesses of inlet guide vanes, for inlet guide vanes at two axial locations, with and without flow turning, and over a range of rotor speeds, pressure ratios, and airflows.

The work contained in this report represents the initial results of a unique research compressor designed in such a manner that its internal configuration can be easily changed to represent a wide range of operating conditions.

SYMBOLS

D_f diffusion factor

M Mach number

$p_{t,1}$ barometric pressure, inches of Hg (millimeters of Hg)

$p_{t,2}$ compressor discharge pressure, inches of Hg (millimeters of Hg)

Δp difference between the barometric pressure and the inlet static pressure, inches of H_2O (millimeters of H_2O)

U rotational velocity, feet/second (meters/second)

V absolute air velocity, feet/second (meters/second)

V_R relative air velocity, feet/second (meters/second)

α absolute air angle, degrees

β relative air angle, degrees

Subscripts:

1 inlet

2 outlet

R relative

x axial direction

θ tangential direction

Abbreviations:

dB decibels, re 0.0002 μ bar

FBPF first rotor blade passage frequency, rpm $\times \frac{23}{60}$, hertz

IGV inlet guide vane

OASPL overall sound pressure level (500 to 25 000 hertz), decibels

SPL sound pressure level, decibels

APPARATUS AND PROCEDURES

Description of Research Compressor

The experimental compressor used in the present studies was manufactured especially for noise research studies and is shown in figures 1, 2, and 3. It is an axial-flow machine having a design airflow of 25 lb/sec (11.32 kg/sec) at a pressure ratio of 3. It has three rotor stages designed for transonic operation with a design corrected rotational speed of 24 850 rpm. The maximum power absorbed by the compressor is 2350 hp (1752 kW). The compressor has a design rated efficiency of 82 percent. It is designed to operate as a one- two- or three-stage machine, and provision is made for changing the number of rotor blades and stator vanes. The three-stage transonic configuration was used in this investigation. The rotor blades have double circular-arc airfoil sections having root and tip diameters of 6 and 12 in. (152.4 and 304.8 mm), respectively, at the entrance to the first-stage rotor. There are 23 blades in the first-stage rotor. Design data, including vector diagrams, for the first stage are presented in tables I and II. Design data are presented for three radial stations for the first rotor and first stator.

The two sets of guide vanes used consisted of symmetrical airfoils that tapered in chord length from about 0.8 in. (20.32 mm) at the root to 1.5 in. (38.10 mm) at the tip. The thickness-chord ratio for the first set was 0.12 and for the second set was 0.06; the first set and second set of vanes are referred to as the 0.12 inlet guide vanes and the 0.06 inlet guide vanes, respectively. The inlet guide vanes are located at axial distances of 1/2 or 5 mean guide-vane chords ahead of the rotor.

The compressor is included in the setup shown schematically in figure 1, which includes a bellmouth inlet, a downstream radial diffuser, and back-pressure control valves (not shown in figure) for adjusting the overall pressure ratio. The compressor is driven by means of a 3000-hp (2237-kW) variable-speed (up to 6600 rpm) electric motor through a 4 to 1 speed increaser.

The setup is arranged so that the noise from the compressor inlet radiates into the anechoic test cell of the Langley noise research laboratory. The photograph in figure 2 shows the compressor inlet and a portion of the 25- by 25- by 23-ft (7.62- by 7.62- by 7.01-m) anechoic test cell prior to sealing around the compressor. As can be seen in the photograph, the test-cell walls are treated with fiber-glass wedges to minimize reflected noise. Additional details regarding the anechoic chamber are contained in the appendix of reference 3. The air for the compressor is brought into the test chamber through a treated inlet stack in the chamber ceiling and is discharged from the radial diffuser through an acoustically treated exhaust stack.

Noise Instrumentation and Measurement

Six 0.5-in.- (12.7-mm-) diameter condenser microphones were used to measure the noise radiation patterns from the compressor. Output signals were recorded on a multichannel magnetic-tape recorder. The overall frequency response of the recording system was flat within ±2 dB from 500 Hz to 40 000 Hz. The entire sound-measurement system was calibrated before and after data collection by means of conventional discrete-frequency calibrators. Prior to acoustical instrumentation installation, a frequency-response check was made on all microphone systems by use of the electrostatic principle. The upper frequency limit was high enough to permit analyses of the fourth-order harmonic of the first-stage rotor-blade passage frequency at 100 percent speed. The microphones were located as shown in figure 4, and the bulk of the data was obtained at a distance of 10 ft (3.05 m) from the inlet bell. Some of the microphones were used on a traveling boom for traversing 0° to 90° about the compressor center line in the horizontal plane to obtain sound radiation patterns. Stationary microphones provided data for 1/10-octave spectrum analyses. Generally, the microphones were set at the same elevation as the compressor center line and with their diaphragms in the vertical plane (0° incidence).

Compressor Operating Procedures

After routine starting procedures were performed, the compressor speed was increased to 70 percent corrected speed (17 395 rpm). At this setting, the back-pressure valves (primary and vernier) were partially closed in order to give a realistic operating condition, that is, reasonable compressor efficiencies. After all temperatures and pressures stabilized, the compressor was considered to be operating at thermodynamic equilibrium. Performance and noise data were taken during a 5-minute stabilized run. To obtain other operating conditions at this speed, the back-pressure valves were closed in even pressure-change increments. At each different back-pressure setting, noise and performance data were collected.

The same procedure was repeated for other corrected speeds up to 100 percent (24 850 rpm). To locate the surge point for any particular speed, the back-pressure valves were closed slowly until a distinct "pounding" noise occurred (also evidenced by an abrupt change of the pressure indicators). Just prior to the surge-point condition for a given speed, the discharge pressure and differential pressure, which indicated airflow rate, were read. It was necessary for comparison purposes to determine the location of points on the surge line for several speeds, but care was taken to avoid "deep surging." All the data presented for either the choked or unchoked modes of operation involved stable conditions.

Performance Instrumentation and Measurement

Six thermocouple probes were evenly spaced circumferentially in the inlet bellmouth. The outputs from these probes were averaged to obtain the inlet air temperature which was used to determine inlet enthalpy and speed of sound in air. Three static-pressure taps were located at the entrance to the inlet-guide-vane housing as shown in figure 3. The average output of these taps and the barometric pressures $p_{t,1}$ were used to obtain values of $\Delta p/p_{t,1}$ which in turn were used to obtain airflow in lb/sec (kg/sec) from a calibration curve provided by the compressor manufacturer. Discharge total pressures $p_{t,2}$ were obtained from the average of inputs from three pressure probes built into the struts in the discharge section of the compressor. (See fig. 3.) Compressor pressure ratio is $p_{t,2}/p_{t,1}$. Most pressure measurements were read from manometers. Discharge temperatures were obtained from thermocouple probes built into the discharge section of the compressor. Enthalpies of the air leaving the compressor were determined by making use of the average discharge temperatures. Compressor efficiencies were determined by using the inlet and outlet enthalpies found from inlet and outlet temperatures and isentropic enthalpies determined by use of the pressure-ratio values. Compressor rotational speed was determined by use of an inductance pickup and was displayed on an electronic counter. Values of average power input to the variable-frequency drive motor were read directly from a kilowatt meter.

RESULTS AND DISCUSSION

The main variables of the tests were rotor speed, compressor pressure ratio, inlet-guide-vane thickness, inlet-guide-vane angle, and inlet-guide-vane axial position. For each test condition, overall noise levels, radiation patterns, noise spectra, and performance measurements were obtained. Of particular significance was the fact that by proper variation of the inlet-guide-vane thickness or inlet-guide-vane angle, the compressor could be operated in a choked flow mode, where the choking occurred in the inlet guide vanes.

Noise Measurements

Spectra for 0.12 inlet guide vanes.- A sample 1/10-octave band noise spectrum for the compressor at 30° azimuth is shown in figure 5 for the 0.12 inlet guide vanes at the 1/2-chord axial location. The data shown in figure 5(a) relate to the 80-percent-speed condition and represent unchoked operation. The spectrum contains both broad-band and discrete-frequency components. The highest peak in the spectrum is at the blade passage frequency of the first rotor. It should be noted that the first blade passage frequency is calculated from the actual rotational speed which varies from run to run as corrected rotational speed is held at a fixed value as temperature varies for performance comparisons. Figure 5(b) is a sample 1/10-octave band noise spectrum at 98 percent speed and represents choked operation. Comparison of figure 5(b) with figure 5(a) shows a 36-dB reduction in the noise level of the first rotor blade passage frequency.

Radiation patterns.- Radiation patterns were obtained for two thicknesses of guide vanes.

0.12 inlet guide vanes: The data of figure 6 were obtained with the use of a traversing microphone in the front quadrant from 0° (on the axis) to 90°. These data are for the compressor at 80 percent speed, with 0.12 inlet guide vanes at 0° guide-vane angle and 1/2-chord axial location. Radiation patterns are shown for the overall sound pressure level and for the blade passage frequency of the first rotor. The radiation patterns have a maximum in the vicinity of 37° azimuth. The discrete-frequency sound-pressure-level radiation pattern is similar in shape to that of the overall noise level and is noted to be the main component over the entire azimuth range of the study. These are characteristic of most radiation patterns of this compressor for unchoked operation.

The dramatic effects of choking in the same inlet guide vanes are shown in figure 7. In this figure are shown the overall-sound-pressure-level radiation pattern for the 80-percent-speed operating condition as in figure 6 and that for the 92- to 100-percent-speed condition for which, as is discussed in more detail later in the paper, the flow is choked in the inlet guide vanes. It can be readily seen that overall sound pressure levels which are 25 to 30 dB lower are associated with the choked-flow operation. An inspection of spectra for the choked-flow condition indicated the presence of broad-band noise with no identifiable discrete tones at any azimuth angle.

0.06 inlet guide vanes at +15^{o} guide-vane angle: An alternate method of choking in the inlet guide vanes consists of turning the guide vanes in a direction opposed to the rotor rotation. This turning does two things: first, the net area for airflow is slightly reduced, and second, the rotor induces slightly more airflow. The combination of these two facts allowed the test compressor to become choked at an inlet-guide-vane angle of +15^{o}, 100 percent speed, and an airflow of 106 percent of the design value.

Figure 8 is a comparison of overall noise radiation patterns for choked (100 percent speed) and unchoked (70 percent speed) operation. The data shown are for 0.06 inlet guide vanes at an inlet-guide-vane angle of +15^{o} and at a 1/2-chord axial location. Comparison of figure 8 and figure 7 demonstrates the comparable noise-reduction benefits of choking by setting of the inlet-guide-vane angles. In both figures, noise reductions on the the order of 25 to 30 dB in the overall sound pressure level were obtained.

Maximum overall sound pressure levels.- The effects of guide-vane configuration and of Mach number were studied.

Effect of vane angularity for 0.06 inlet guide vanes: Data of the type illustrated in figure 8 were obtained for a range of compressor speeds and inlet-guide-vane angular positions (for the 0.06 inlet guide vanes at the 1/2-chord axial location), and the results of those tests are summarized in figure 9. The measured values of the maximum overall sound pressure levels, regardless of the azimuth angles at which they occur, are plotted as a function of design corrected compressor rotor speed. The maximum overall sound pressure levels usually occur at azimuth angles from 15^{o} to 45^{o} for the ranges of operations of this study. Data are shown for three angular positions of the inlet guide vanes at 1/2 mean guide-vane chord ahead of the rotor. The circular data points relate to the vanes alined in the axial-flow direction (guide-vane angle of 0^{o}). The square data points relate to the guide-vane angle of -15^{o} for which the flow is turned in the direction of rotation of the first-stage rotor, a condition representative of many current compressor designs. The diamond data points relate to the guide-vane angle of +15^{o} for which the flow is turned opposite to the direction of rotation of the blades. It can be seen that the noise-reduction effects at increased rotor speed are relatively small at the lower speeds but are dramatic at the higher speeds. For the inlet-guide-vane angle of -15^{o}, the noise levels are generally the same as speed increases, whereas for the guide-vane angles of 0^{o} and +15^{o}, the noise levels generally decrease. These decreases are thought to be due to the effects of either partial choking or complete choking in the inlet guide vanes. For the inlet-guide-vane angle of +15^{o}, there is an increase in the mass flow through the inlet which is sufficient to cause complete local choking of this flow at the inlet guide vanes. At 100 percent speed the blockage areas of the inlet guide vanes are identical for a $+15^{\circ}$ and -15° angularity because of geometric symmetry, and hence the choking occurs at the $+15^{\circ}$ conditions mainly because of the associated increased velocity through the guide vanes. A limitation of this method of choking would be possible flow separation and the attendant instabilities if the inlet-guide-vane angle exceeded the stall angle of attack.

Effect of vane axial location for 0.06 inlet guide vanes: The data of figure 9 relate to the 0.06 inlet guide vanes located in close proximity to the rotor (1/2-chord). Similar data were obtained when the inlet guide vanes were moved approximately 5 chords upstream of the rotor. The data obtained for these two inlet-guide-vane positions and data obtained with inlet guide vanes removed are compared in figure 10. It is obvious that the increased inlet-guide-vane spacing is beneficial in reducing the maximum overall sound pressure levels at the lower speeds for which no flow choking occurs. This effect is expected on the basis of the work of references 4 and 5 because of effects of the reduced inlet-guide-vane—rotor interaction for the larger spacing. This result suggests that the inlet-guide-vane—rotor interactions are relatively weak for the increased spacing and thus are consistent with results of references 4 and 5.

As the rotor speed is increased to the rated value, noise reductions associated with the choking of the inlet guide vanes are seen not to be dependent on the inlet-guide-vane spacing. This result suggests that the mechanism for noise reduction is the flow choking and the interaction noise is thus essentially blocked from radiation out of the inlet. It is significant that the presence of the guide vanes results in noise levels considerably lower than when the inlet guide vanes were not present.

Comparison of effects of inlet-guide-vane thickness: Data of the type illustrated in figures 7 and 8 were obtained for a range of compressor speeds and inlet configurations, and the results of some of these tests are plotted in figure 11 to show the effect of inlet-guide-vane thickness. Data are shown for four configurations: 0.12 guide vanes set at 0°, spaced 1/2 chord from the rotor; 0.06 guide vanes set at 0°, spaced 1/2 chord from the rotor; 0.06 guide vanes set at $+15^{\circ}$, spaced 5 chords from the rotor; and no guide vanes. The curve representing the 0.12 guide vanes does not begin to show any appreciable attenuation in noise until about 85 percent speed. However, after this point the noise reduction is quite rapid as speed is increased and attains a minimum at 92 percent speed. The data in this plot show that a reduction of about 27 dB is attained from the 0.12-guide-vane configuration. The flat portion of this curve represents completely choked flow. Further increases in rotational speed had no effect on either the noise or the airflow. The configuration of 0.06 guide vanes with 0° vane setting and 1/2-chord axial location has the highest overall sound pressure level, particularly at the higher speeds. The 8-dB decrease at the higher speed of this curve is thought to be associated with a partial choking condition. The calculated average axial Mach number for one-dimensional flow in the inlet guide vanes at this point is 0.83. The curve representing 5-chord axially spaced, 0.06 guide vanes, with +15° vane setting shows a large (8 dB) noise reduction at low speed and a maximum noise reduction at high speed, that is, completely choked flow. The configuration with no inlet guide vanes results in a 10 dB reduction at the lowest speed as compared with the 0.06 guide vanes with 0° setting and 1/2-chord spacing. This type of noise reduction is well known as shown in references 4 and 5, and some jet engines are currently being built without inlet guide vanes because of this noise-reduction benefit. The 4-dB decrease at the high-speed end of the no-guide-vane curve is thought to represent a partial choking effect. The average axial Mach number for one-dimensional flow at this point is 0.65.

Mach number effects for 0.12 inlet guide vanes: Maximum overall sound pressure level is plotted as a function of axial Mach number in the inlet guide vanes in figure 12 for the 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord spacing. These data were taken at the 30° azimuth location 10 ft (3.05 m) from the inlet bellmouth. From this plot it is seen that noise attenuation due to higher Mach numbers does not begin until the axial Mach number exceeds 0.65. The gradual decrease is approximately 5 dB for a 0.1 change in Mach number for Mach numbers from 0.7 to 1.0. At Mach 1.0 a sharp drop of 10 dB was experienced. Note that overall sound pressure levels plotted are the maximums recorded. It is evident from this plot that the parameter which directly affects the noise attenuation at high speed is the axial Mach number in the guide vanes.

Variation in sound pressure level.- Typical records of overall sound pressure level as a function of time are shown in figure 13; these recordings were made at the 30° azimuth for the 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord spacing. The record shown in figure 13(a) was made while the compressor was operating in an unchoked mode (80 percent speed). The amplitude varies as much as ±2.5 dB rms in a random manner. Other records not shown indicate that this variation is much the same regardless of the location of the recording microphone. Figure 13(b) shows similar data at the same azimuth location, but with the compressor operating in a choked-flow mode (98 percent speed). These latter variations are seen to be of the order of ±0.5 dB rms; the reduced variability for the choked-flow condition is believed to result from the virtual elimination of pure tones.

Location of transitional shock region.- In order to locate the position of the transitional shock region in the compressor, use was made of a probe microphone. Several positions were surveyed (fig. 3) in the vicinity of the guide vanes. The location of the choked-flow region was determined by analyzing the output of the probe microphone by means of two 1/10-octave spectrum analyses as shown in figures 14(a) and (b); data are for 100 percent speed and for the 0.06 inlet guide vanes, with +10° vane setting and

5-chord spacing. Whenever the first rotor blade passage frequency was present in the spectrum analysis, the sensitive area of the probe was believed to be located downstream of the transitional shock region (fig. 14(a)). Whenever the first blade passage frequency was absent from the spectrum analysis, the probe was believed to be located upstream of the transitional shock region (fig. 14(b)). From an inspection of these spectra it was concluded that the transitional shock region was located at the trailing edge of the inlet guide vanes.

Compressor Performance

In figure 15, compressor efficiency and pressure ratio are plotted as functions of the percent of the design corrected flow for the 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord spacing. Comparison of these curves with the dash-line curves for the 0.06 inlet guide vanes shows the compressor-performance penalties incurred by choking in the 0.12 inlet guide vanes. The primary loss is in pressure ratio. At worst, the maximum pressure ratio is down from 3.02 to 2.82, or 6.6 percent at 95 percent flow. At least, the pressure-ratio losses are down from 1.90 to 1.86, or 2.1 percent at 58.5 percent flow. On the positive side, the maximum compressor efficiencies are essentially equal to those for the 0.06 guide vane. The lines of constant rotational speed are not substantially affected until around 80 percent speed. The shift of the lines to the left at the higher speeds appears to be related to the flow pressure losses caused by the increased thickness of the inlet guide vanes. No comparisons can be made beyond the design choke limitation.

Figure 16 shows performance losses associated with the 0.06 guide vanes turned $+15^{\circ}$ at the 1/2-chord spacing. Curves for the 0° setting are shown as dash lines. Again, the primary loss is in pressure ratio. The maximum pressure ratio is down from 3.10 to 2.86 or 7.7 percent at 100 percent speed and down from 1.97 to 1.82 or 7.6 percent at 60 percent flow. In this figure, the lines of constant rotational speed are shifted to the right at the higher speeds. This opposite shift, as compared with the results for the 0.12 guide vane (fig. 15), appears to be due to the predominance of the increased aerodynamic ability of the compressor to induce more airflow at a given rotational speed. The maximum compressor efficiencies for the 0.06 guide vane turned $+15^{\circ}$ are below the standard case of 0.06 guide vanes at 0° by about 6 percent at 100 percent speed, 7 percent at 90 percent speed, 10 percent at 80 percent speed, and 10 percent at 70 percent speed.

In order to have maximum noise reductions a configuration that would produce choked flow, that is, inlet-guide-vane angularity or thickened inlet guide vanes, is required, whereas for maximum performance the original design inlet guide vanes need to be present. Therefore, a case for variable-geometry inlet guide vanes is established. Also, it should be evident that choked flow, and hence maximum noise reductions, can be obtained at any speed setting of the compressor with variable-thickness inlet guide vanes. It should be noted that the performance losses quoted are considered relatively insignificant if choking is employed during an airplane landing-approach mode.

CONCLUDING REMARKS

An investigation has been conducted to determine the effects of inlet-guide-vane choking on compressor performance and radiated inlet noise from a three-stage transonic axial-flow research air compressor rated at 25 pounds/second (11.32 kilograms/second) of airflow at a pressure ratio of 3. Compressor-performance and noise measurements were made during tests with variable-angle inlet guide vanes and for two inlet-guide-vane thicknesses.

Choking the inlet flow in the guide vanes, by means of either increased guide-vane thickness or flow angularity, was beneficial in reducing the overall sound pressure levels forward of the compressor by 25 to 30 decibels and 36 decibels in the first-rotor-blade-passage-frequency sound pressure level.

There was no measurable compressor-efficiency loss when the inlet was choked by increasing thickness-chord ratio from 0.06 to 0.12, with the 0.12 guide vanes set at 0°. However, there was an average compressor-efficiency loss of 8 percent when the inlet was choked with 0.06 guide vanes set at $+15^{\circ}$. In both cases, there were pressure-ratio losses of 7 to 8 percent. The results of this investigation indicate that inlet guide vanes with variable thicknesses hold the most promise for maximum noise reductions without compressor-performance penalties.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., April 24, 1968,
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TABLE I.- DESIGN DATA FOR FIRST TRANSONIC STAGE

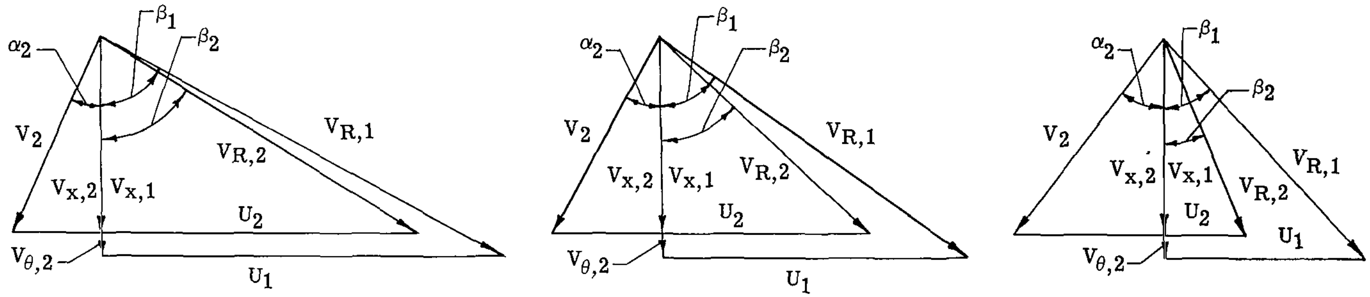
(a) First rotor with 23 blades having double circular-arc airfoil sections

Radius		Chord		Solidity	Turning angle, deg	Thickness, percent chord	Camber angle, deg	Setting angle, deg	Incidence angle, deg	Inlet blade angle, deg	Exit blade angle, deg	Deviation angle, deg
in.	m	in.	m									
5.975	0.1518	1.622	0.0410	0.994	2.50	3.21	0.79	58.56	4.00	58.96	58.16	1.57
4.565	.1160	1.622	.0410	1.301	7.90	3.88	7.60	48.00	4.00	51.80	44.20	3.69
3.155	.0800	1.622	.0410	1.882	27.00	7.77	30.14	26.43	4.00	41.50	11.36	7.15

(b) First stator with 30 blades having NACA 65 series airfoil sections

Radius		Chord		Solidity	Turning angle, deg	Thickness, percent chord	Angle of attack, deg	Setting attack, deg	Isolated airfoil lift coefficient
in.	m	in.	m						
5.930	0.1504	1.206	0.0306	0.971	24.04	4.975	13.7	10.34	1.44
4.695	.1190	1.206	.0306	1.227	29.39	4.975	16.1	13.28	1.538
3.470	.0881	1.206	.0306	1.660	37.35	4.975	21.1	16.05	1.775

TABLE II.- VELOCITY VECTOR DIAGRAMS AND DATA FOR FIRST-TRANSONIC-STAGE ROTOR



$M_{x,1}$	0.624	0.624	0.624
$M_{x,2}$	0.517	0.518	0.523
$M_{R,1}$	1.361	1.099	0.865
$M_{R,2}$	1.040	0.785	0.569
M_2	0.565	0.597	0.668
D_f	0.281	0.356	0.445
U_1	1301 ft/sec (396 m/s)	973 ft/sec (296 m/s)	645 ft/sec (197 m/s)
U_2	1290 ft/sec (394 m/s)	1005 ft/sec (306 m/s)	721 ft/sec (220 m/s)
V_2	644 ft/sec (196 m/s)	678 ft/sec (206 m/s)	752 ft/sec (229 m/s)
$V_{x,1}$	671 ft/sec (204 m/s)	671 ft/sec (204 m/s)	671 ft/sec (204 m/s)
$V_{x,2}$	589 ft/sec (179 m/s)	589 ft/sec (179 m/s)	589 ft/sec (179 m/s)
$V_{\theta,2}$	261 ft/sec (79.5 m/s)	335 ft/sec (102 m/s)	468 ft/sec (143 m/s)
$V_{R,1}$	1464 ft/sec (446 m/s)	1182 ft/sec (360 m/s)	931 ft/sec (284 m/s)
$V_{R,2}$	1185 ft/sec (361 m/s)	892 ft/sec (272 m/s)	644 ft/sec (196 m/s)
α_2	23.9°	29.6°	38.4°
β_1	62.6°	55.3°	43.8°
β_2	60.1°	48.6°	23.2°
Station radius:			
Inlet	6.00 in. (152.4 mm)	4.49 in. (114.0 mm)	2.96 in. (75.2 mm)
Outlet	5.95 in. (152.0 mm)	4.63 in. (117.5 mm)	3.30 in. (83.9 mm)

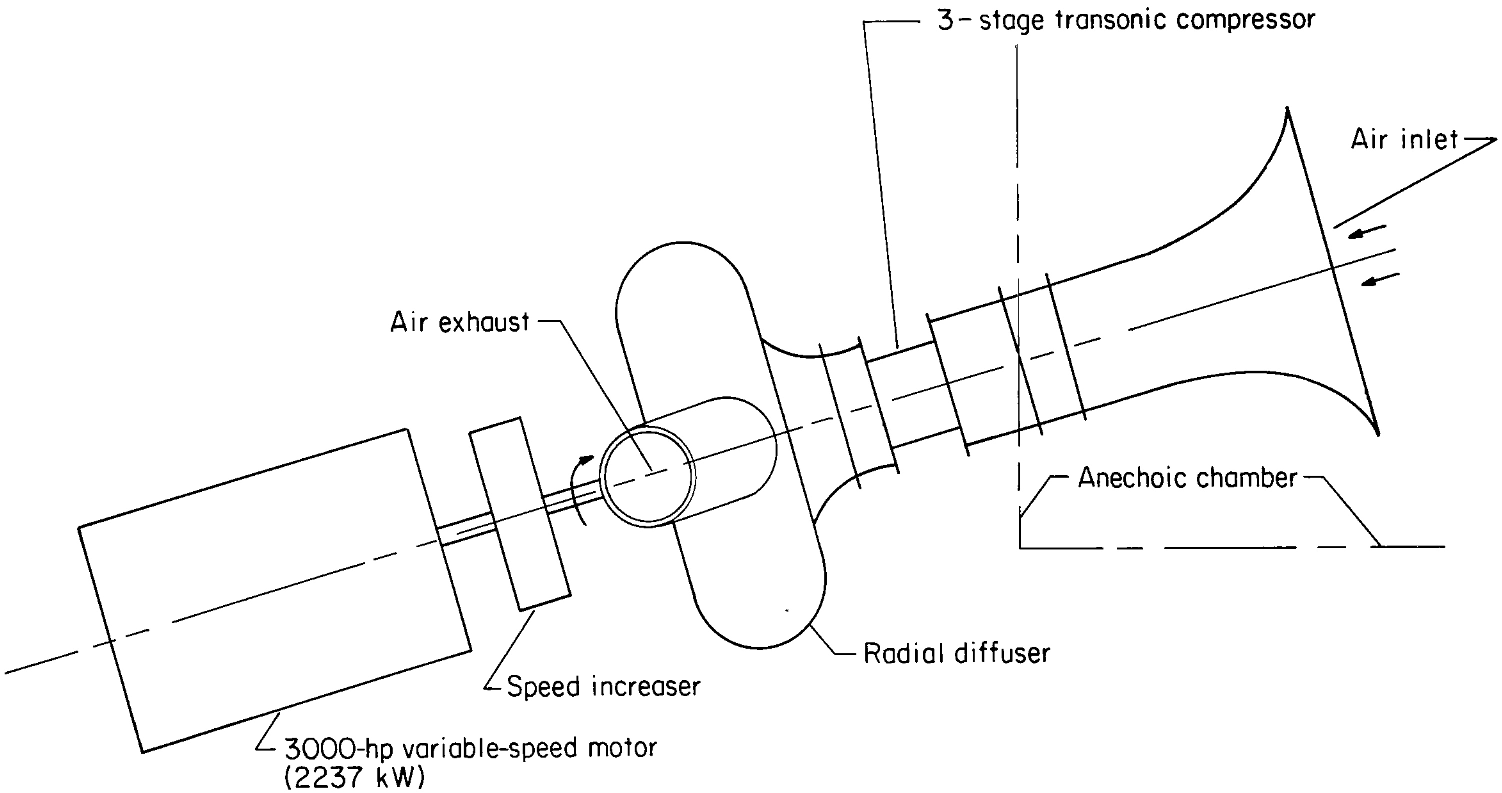


Figure 1.- Schematic diagram (plan view) of compressor installation.

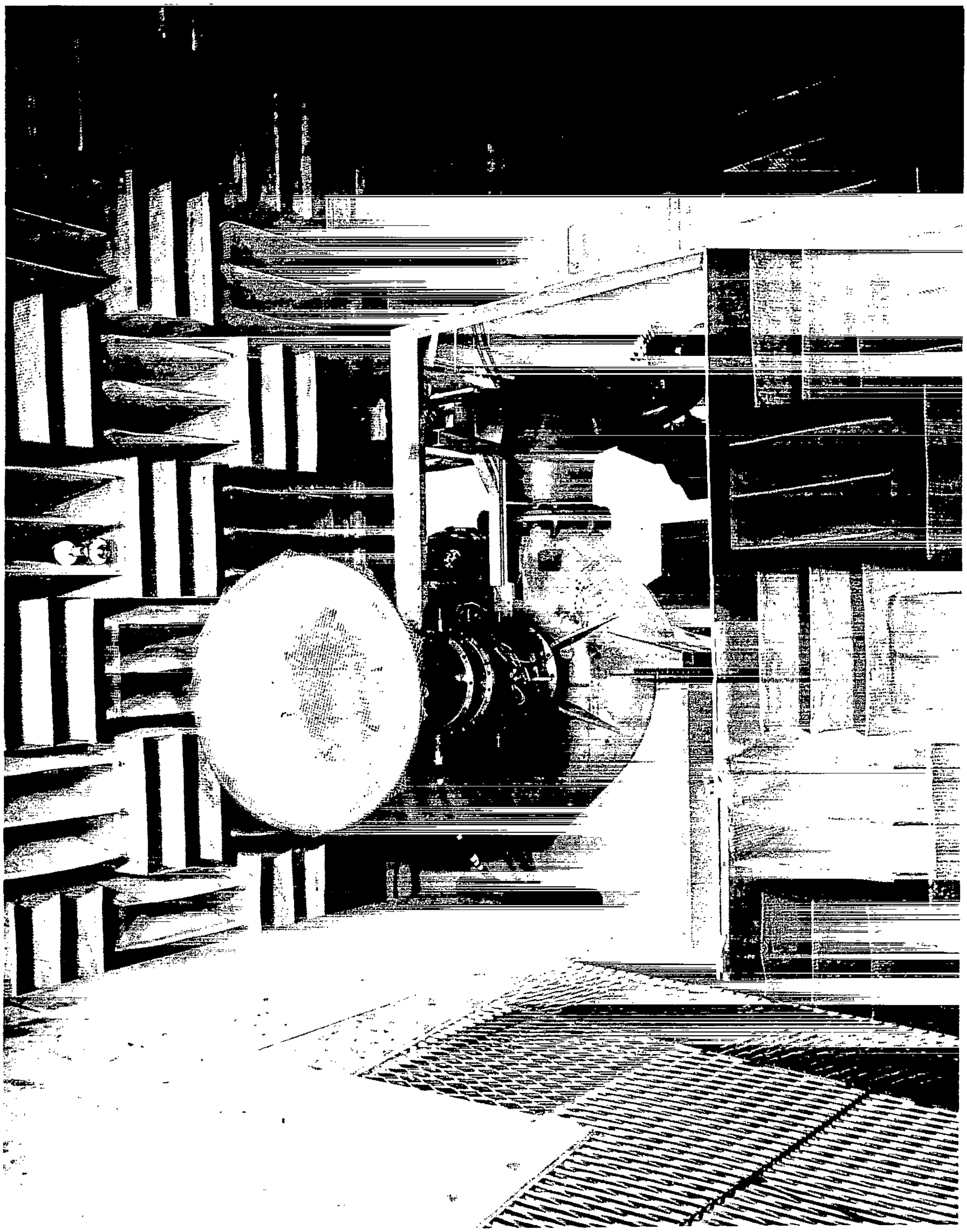


Figure 2.- Photograph of research air compressor in anechoic chamber with wedges removed. L-66-2876

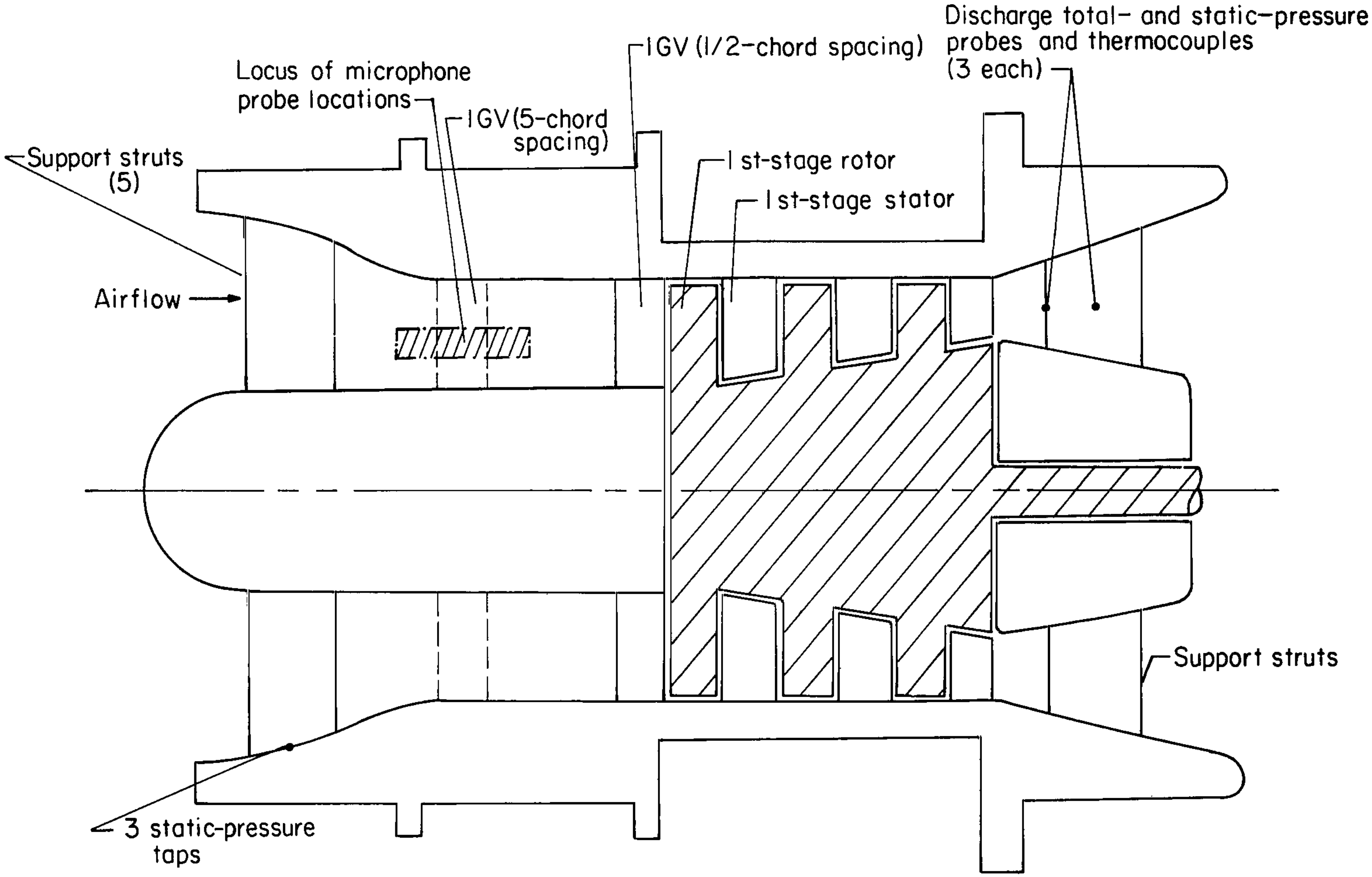


Figure 3.- Cross-sectional sketch of research air compressor.

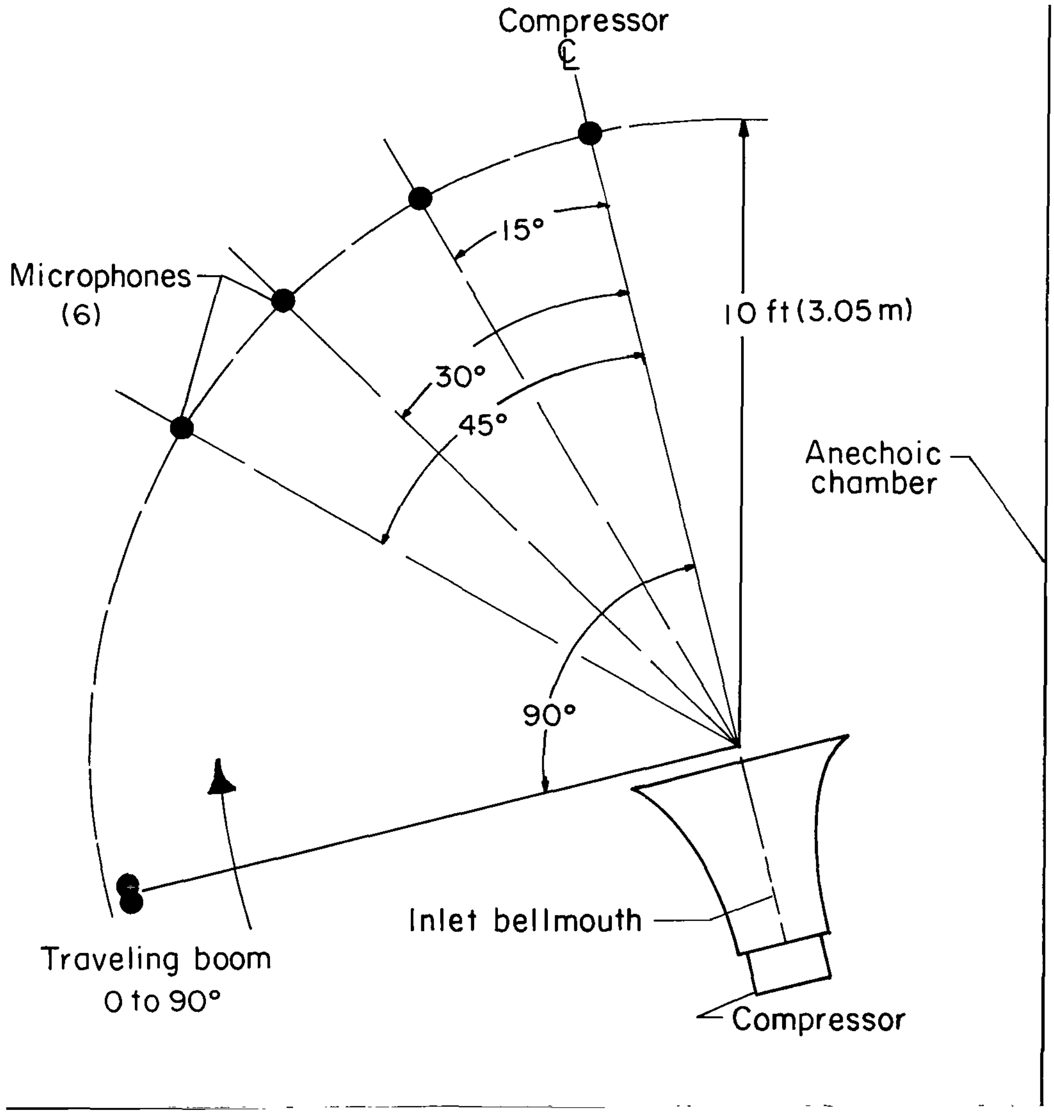
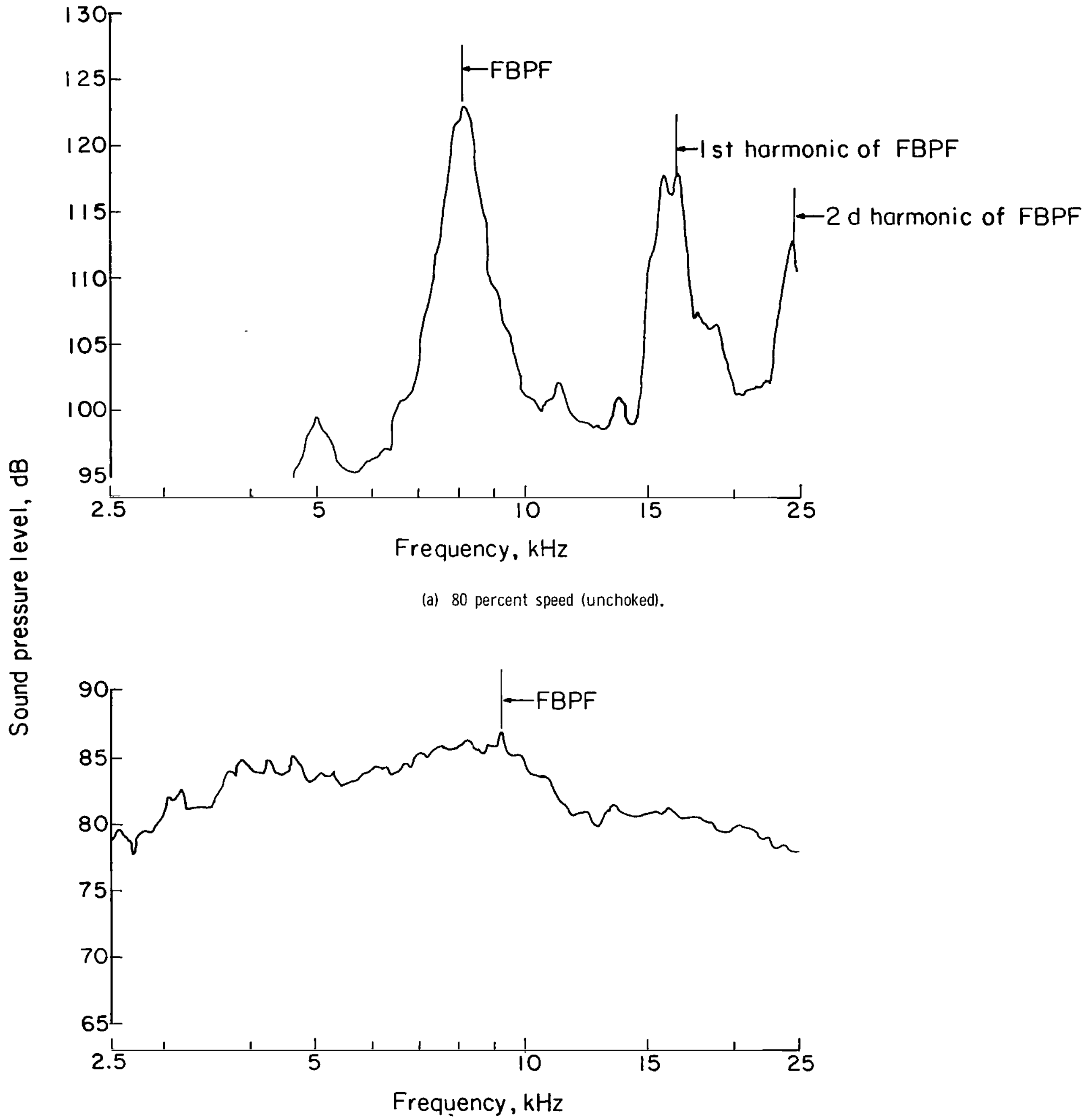


Figure 4.- Typical microphone layout.



(a) 80 percent speed (unchoked).

(b) 98 percent speed (choked).

Figure 5.- 1/10-octave spectrum analysis at 30^0 azimuth. 0.12 inlet guide vanes at 1/2-chord axial location.

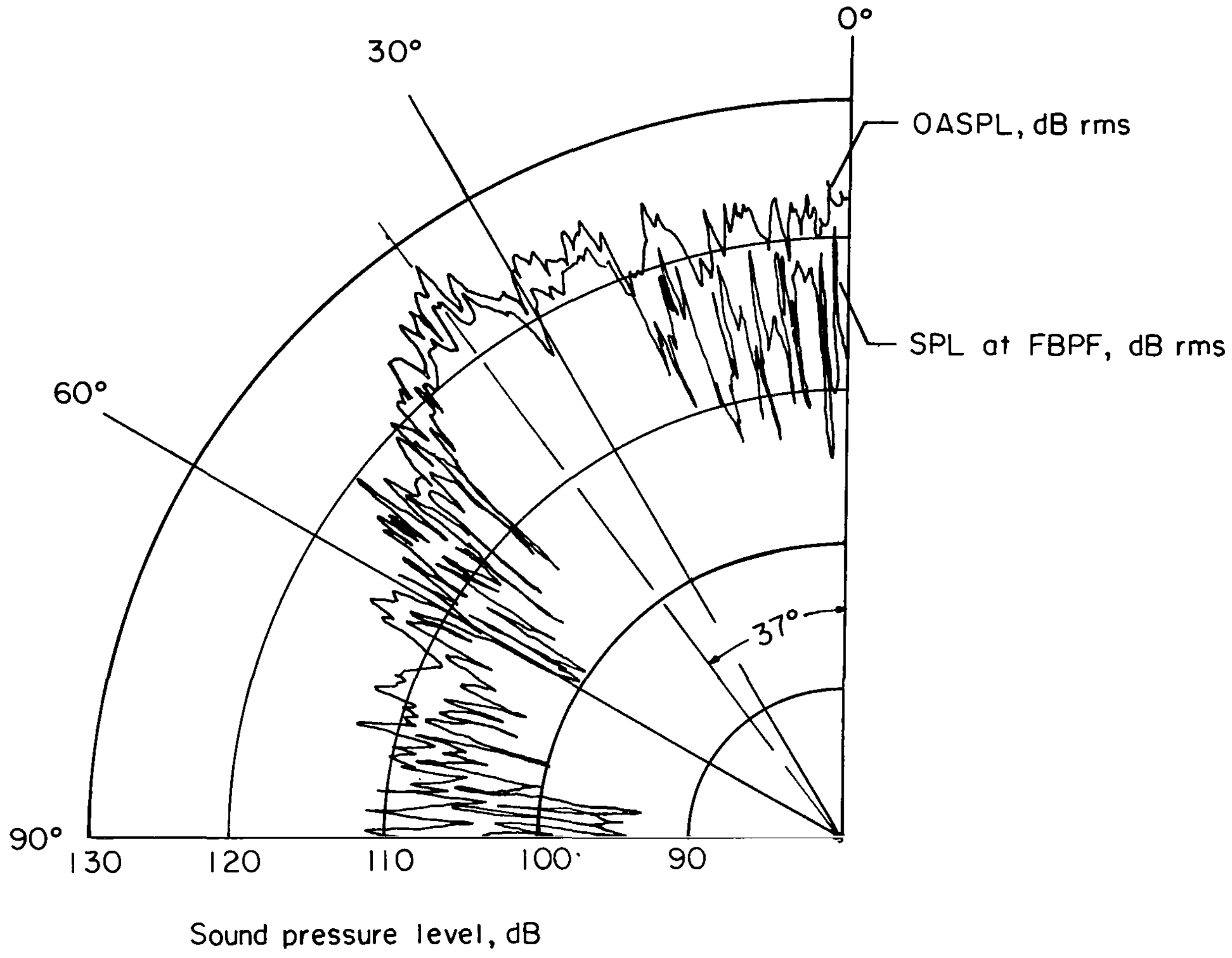


Figure 6.- Sound-pressure-level radiation patterns at 80 percent speed (unchoked). Overall sound pressure level; first-rotor-blade-passage-frequency sound pressure level (1/10-octave analysis at 7670 Hz); typical back-pressure setting; 0.12 inlet guide vanes, with 0^{0} vane setting and 1/2-chord axial location.

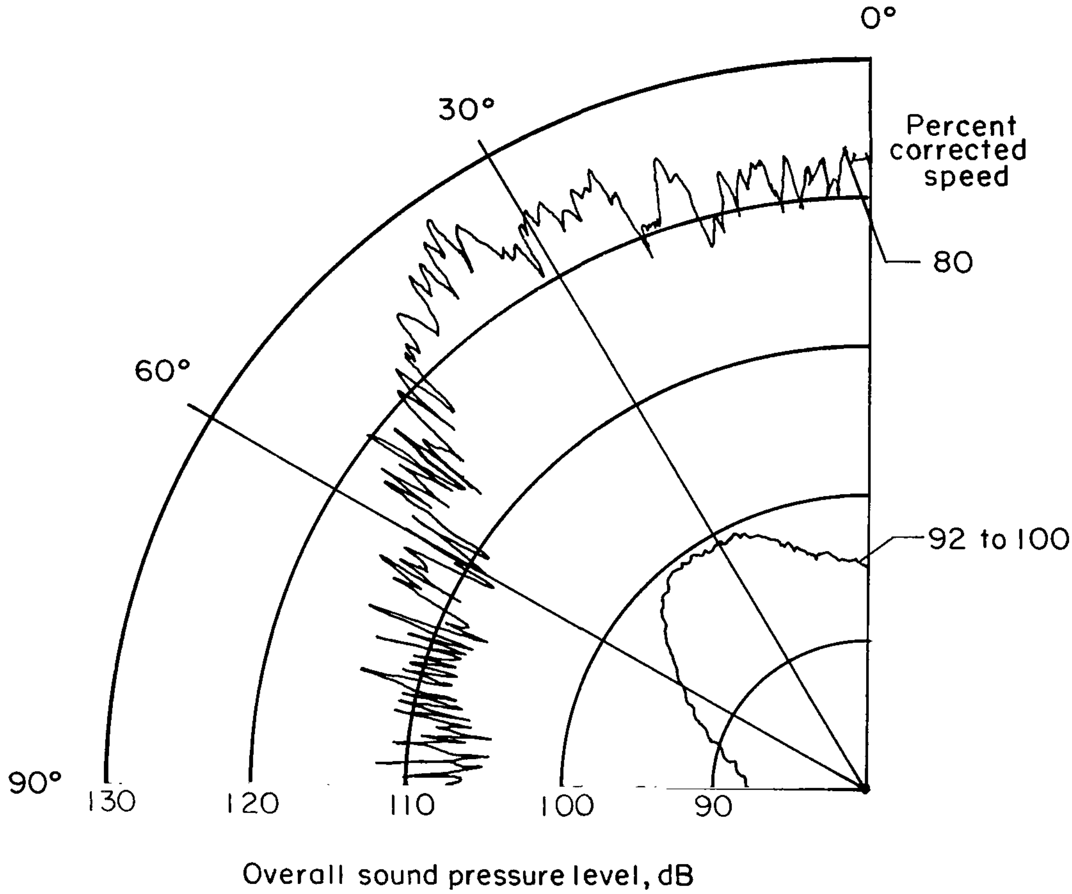


Figure 7.- Comparison of overall-sound-pressure-level radiation patterns of unchoked (80 percent speed) and choked (92 to 100 percent speed) operation. Typical back-pressure settings; 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord axial location.

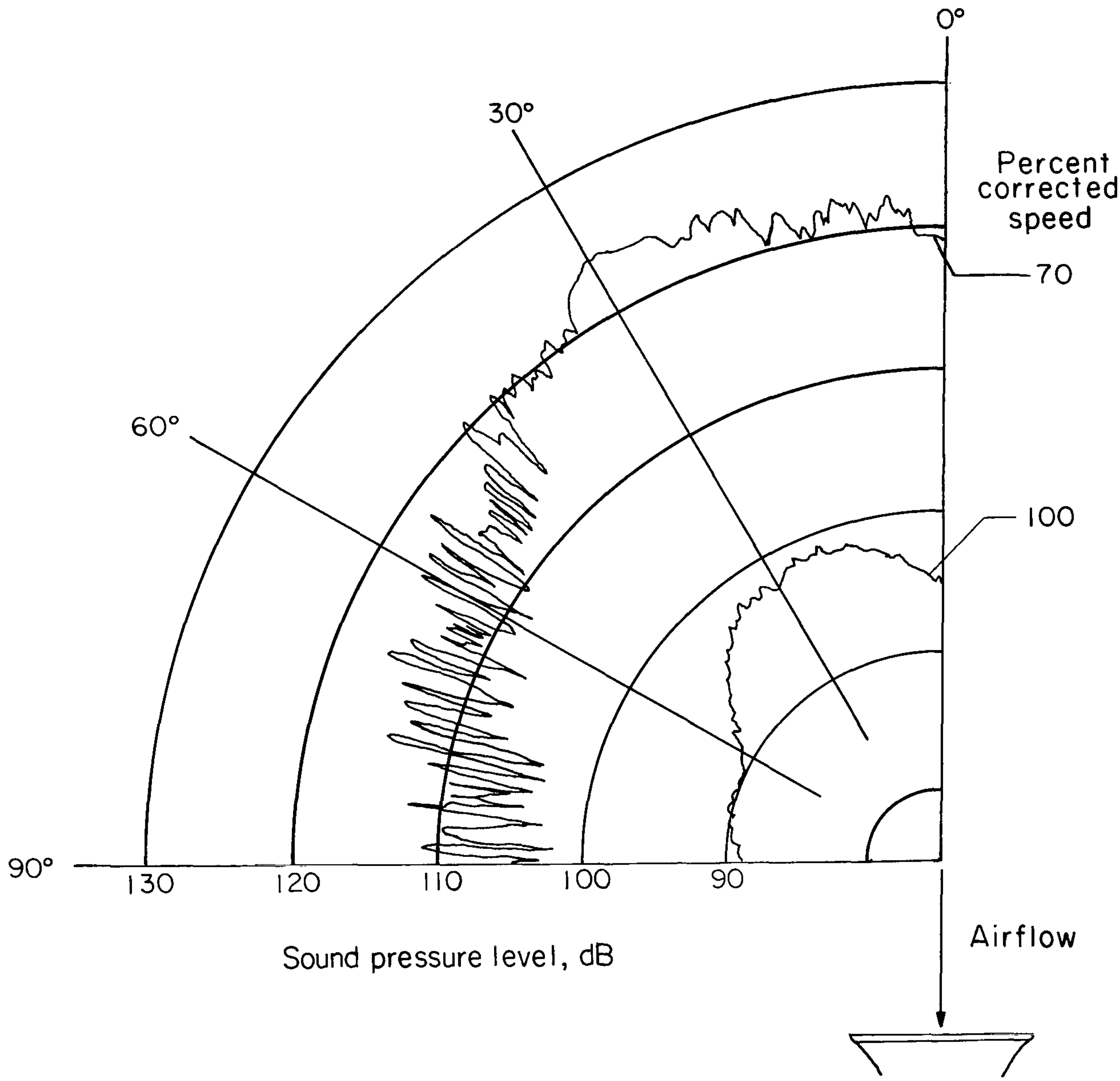


Figure 8.- Comparison of overall-sound-pressure-level radiation patterns for choked (100 percent speed) and unchoked (70 percent speed) operation. Typical back-pressure setting; 0.06 inlet guide vanes, with $+15^0$ vane setting and 1/2-chord axial location.

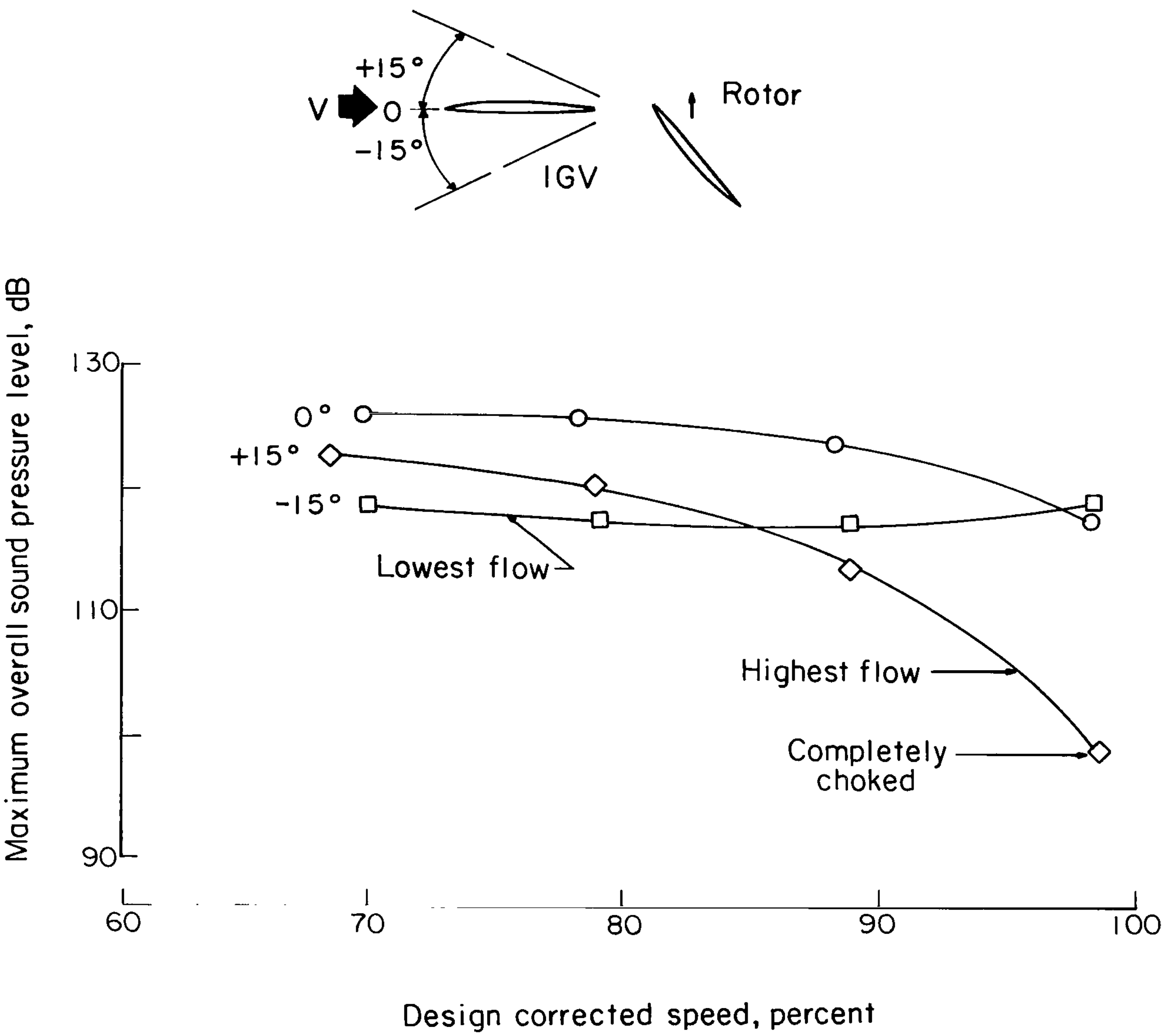


Figure 9.- Maximum overall sound pressure levels as function of corrected compressor speed for three inlet-guide-vane angles. 0.06 inlet guide vanes at 1/2-chord axial location.

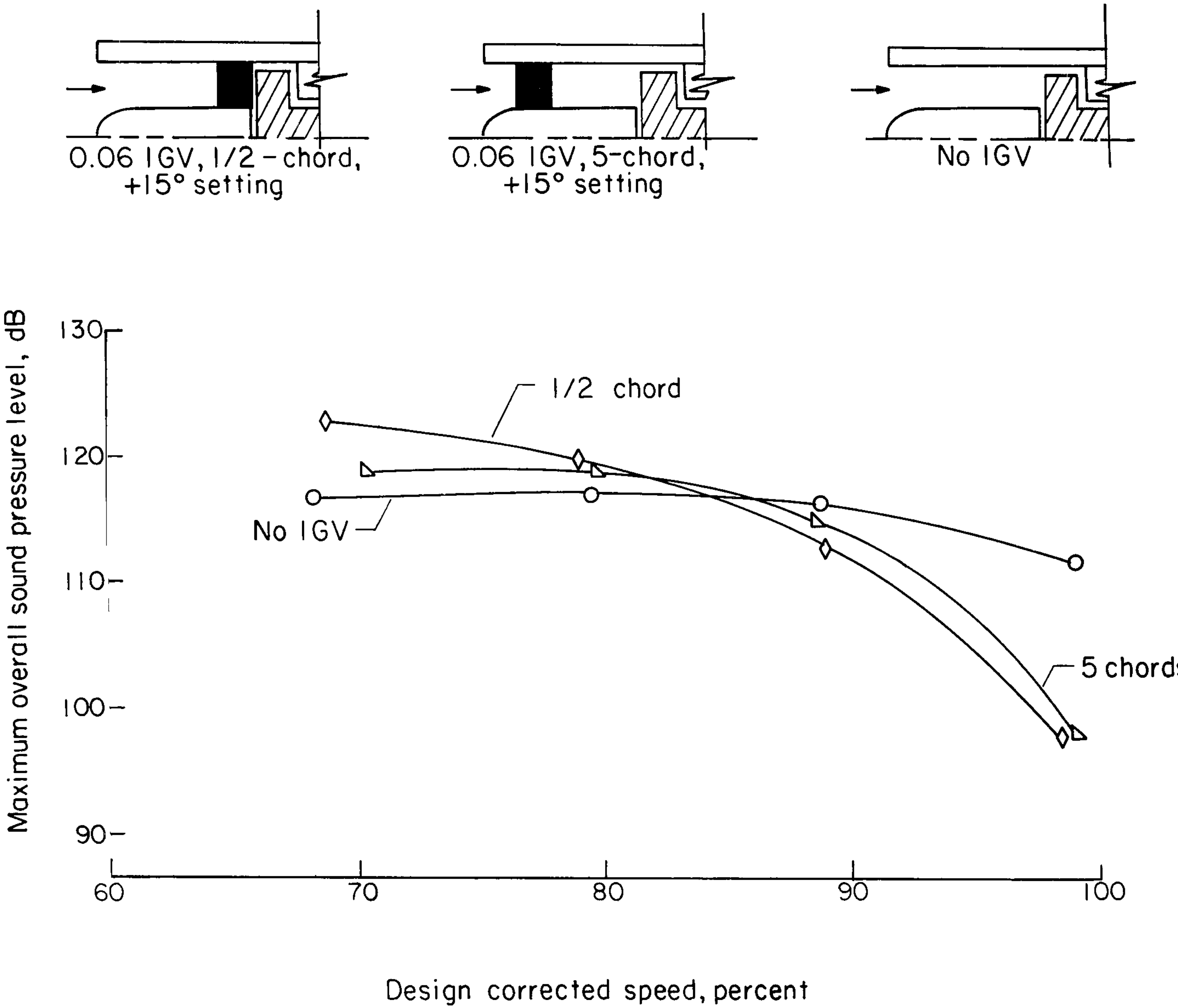


Figure 10.- Maximum overall sound pressure levels as function of corrected compressor speed for two axial locations of 0.06 inlet guide vanes and for inlet guide vanes removed.

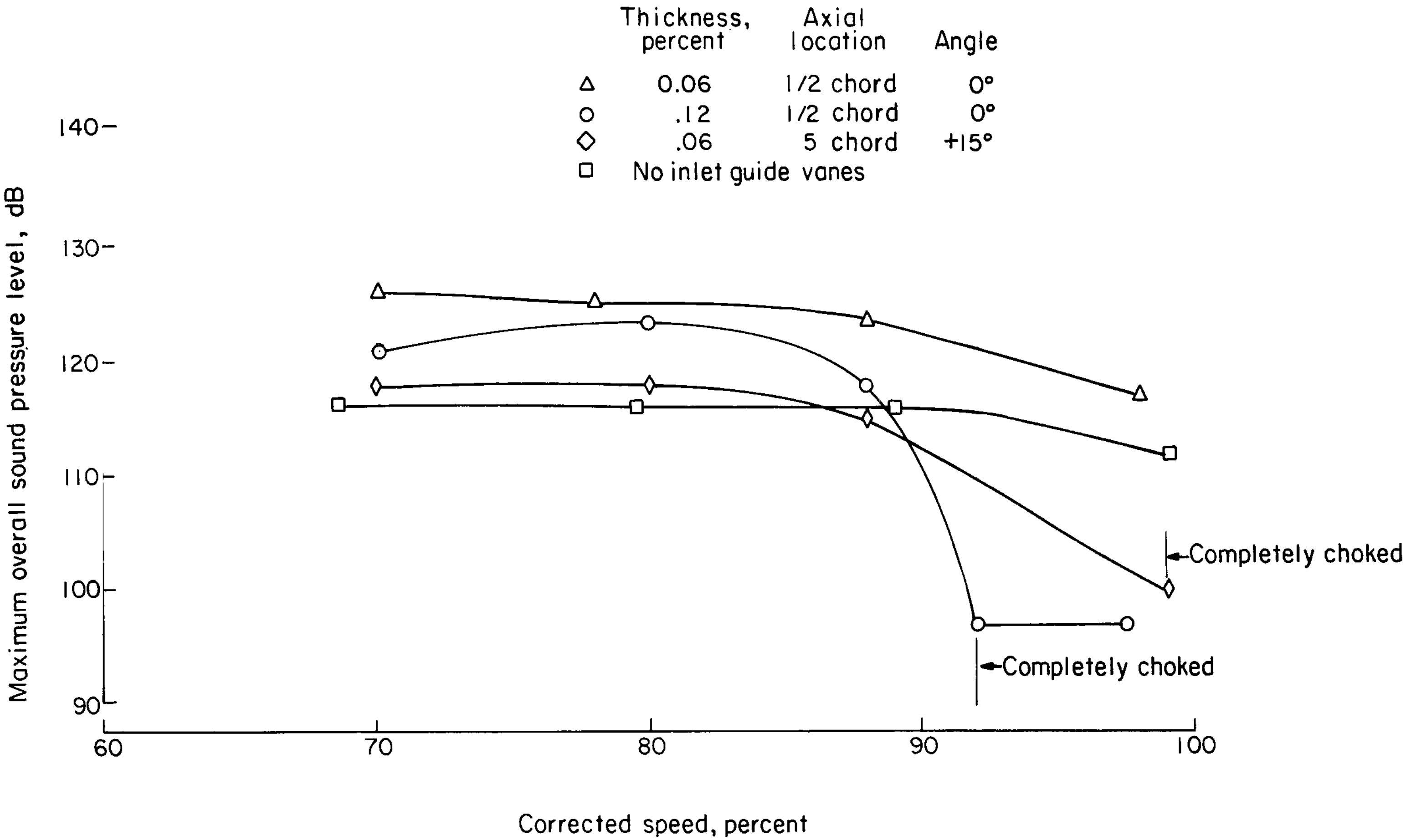


Figure 11.- Maximum overall sound pressure level as function of corrected compressor speed for three inlet-guide-vane configurations and for inlet guide vanes removed.

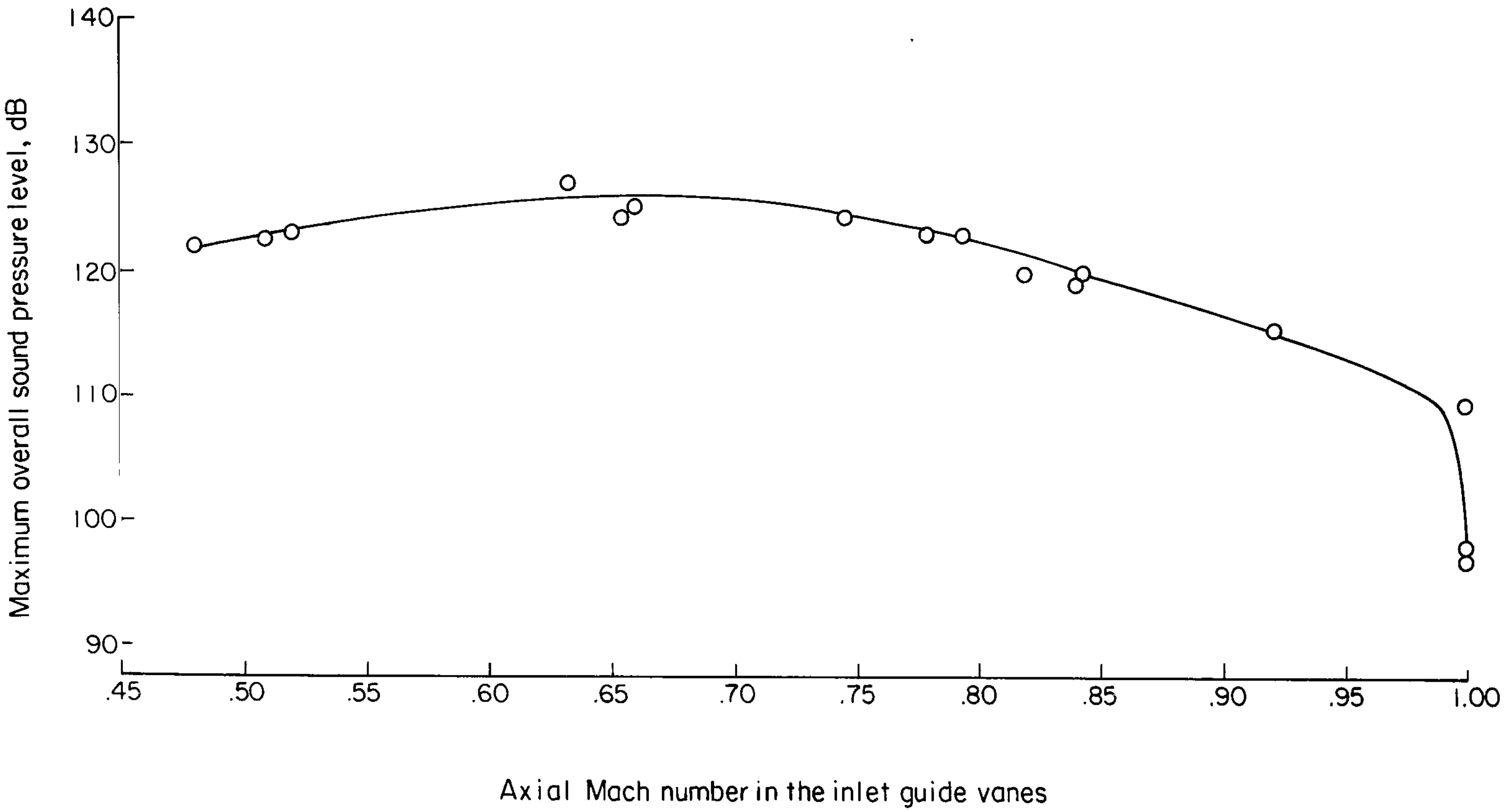
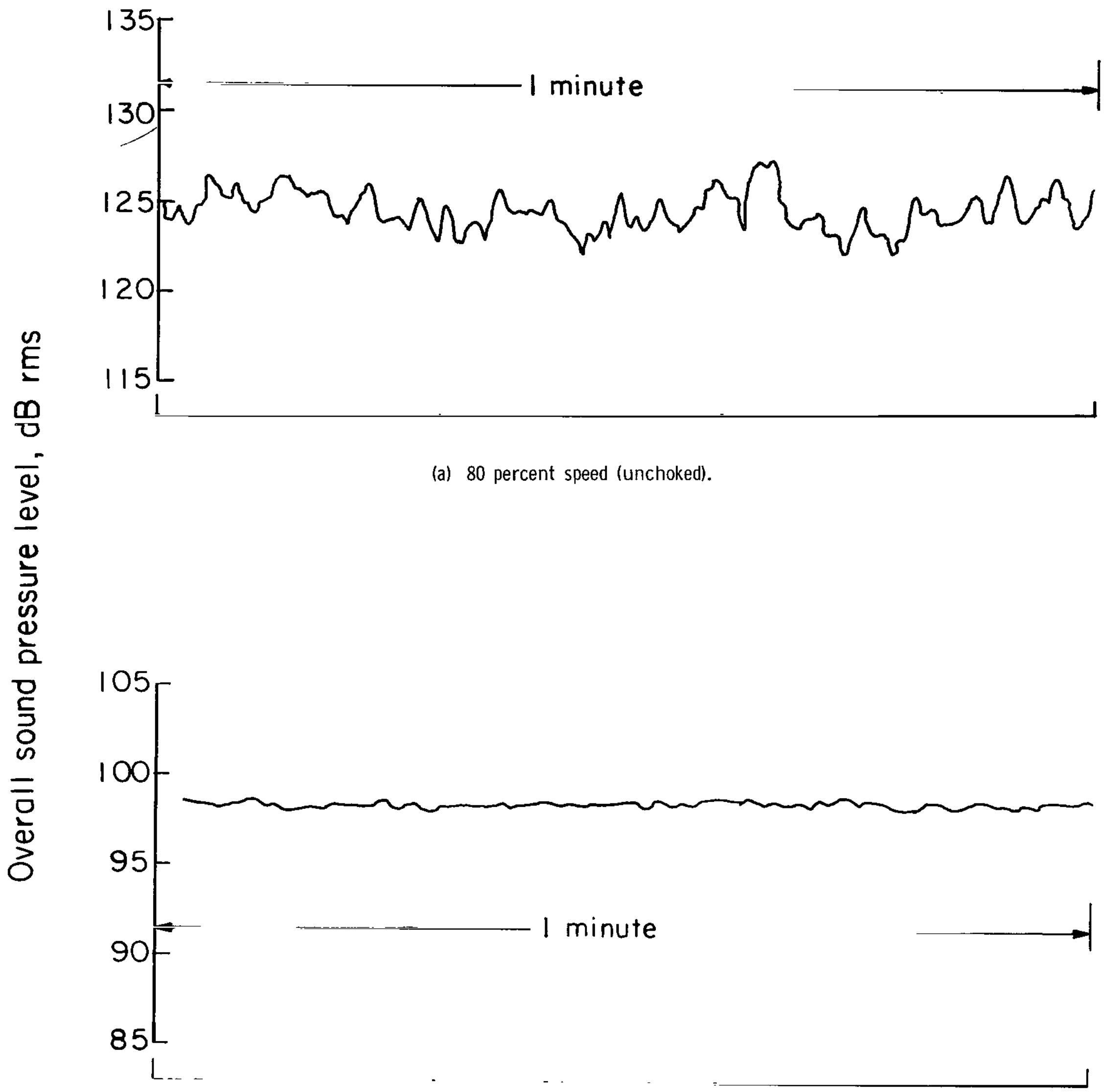


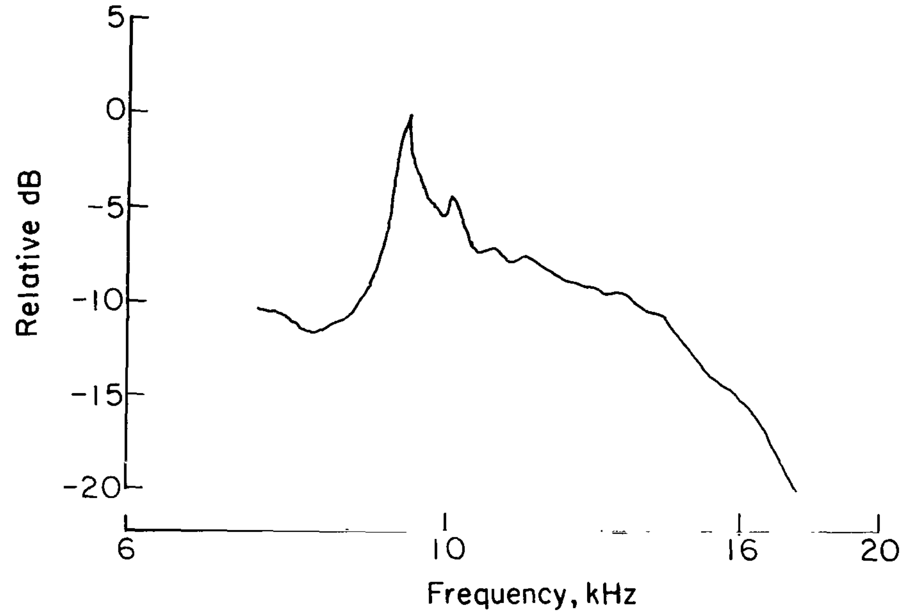
Figure 12.- Effect of axial Mach number in inlet guide vanes on maximum overall sound pressure level at 30° azimuth 10 feet (3.05 meters) from the inlet bellmouth. 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord axial location.



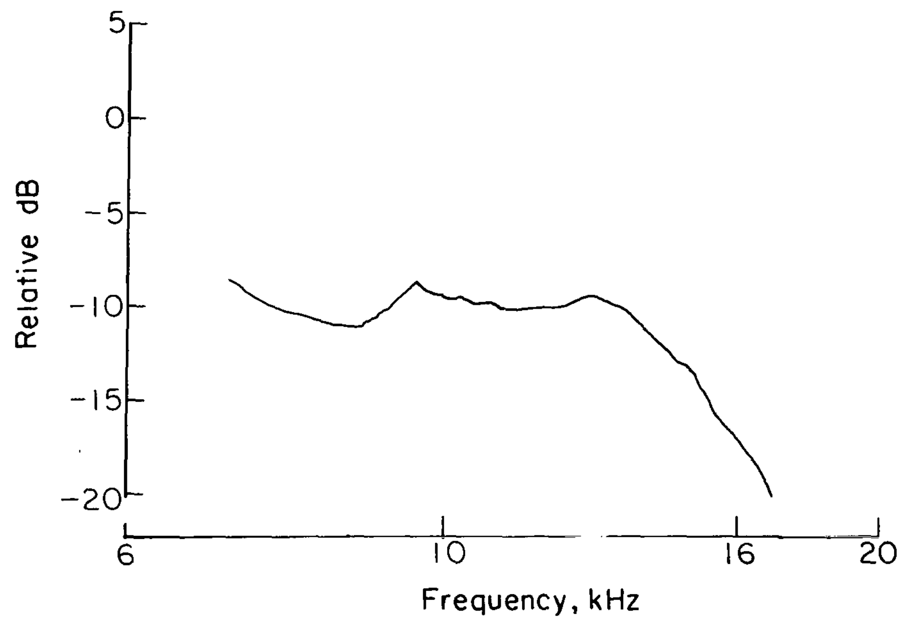
(a) 80 percent speed (unchoked).

(b) 98 percent speed (choked).

Figure 13.- Time history of overall sound pressure level at 30° azimuth. 0.12 inlet guide vanes, with 0° vane setting and 1/2-chord axial location.



(a) 0.25 in. (6.35 mm) downstream of inlet-guide-vane trailing edge.



(b) At inlet-guide-vane trailing edge.

Figure 14.- 1/10-octave band noise spectra at two locations inside inlet duct as obtained with probe microphone. 100 percent speed; 0.06 inlet guide vanes, with $+10^{0}$ vane setting and 5-chord axial location.

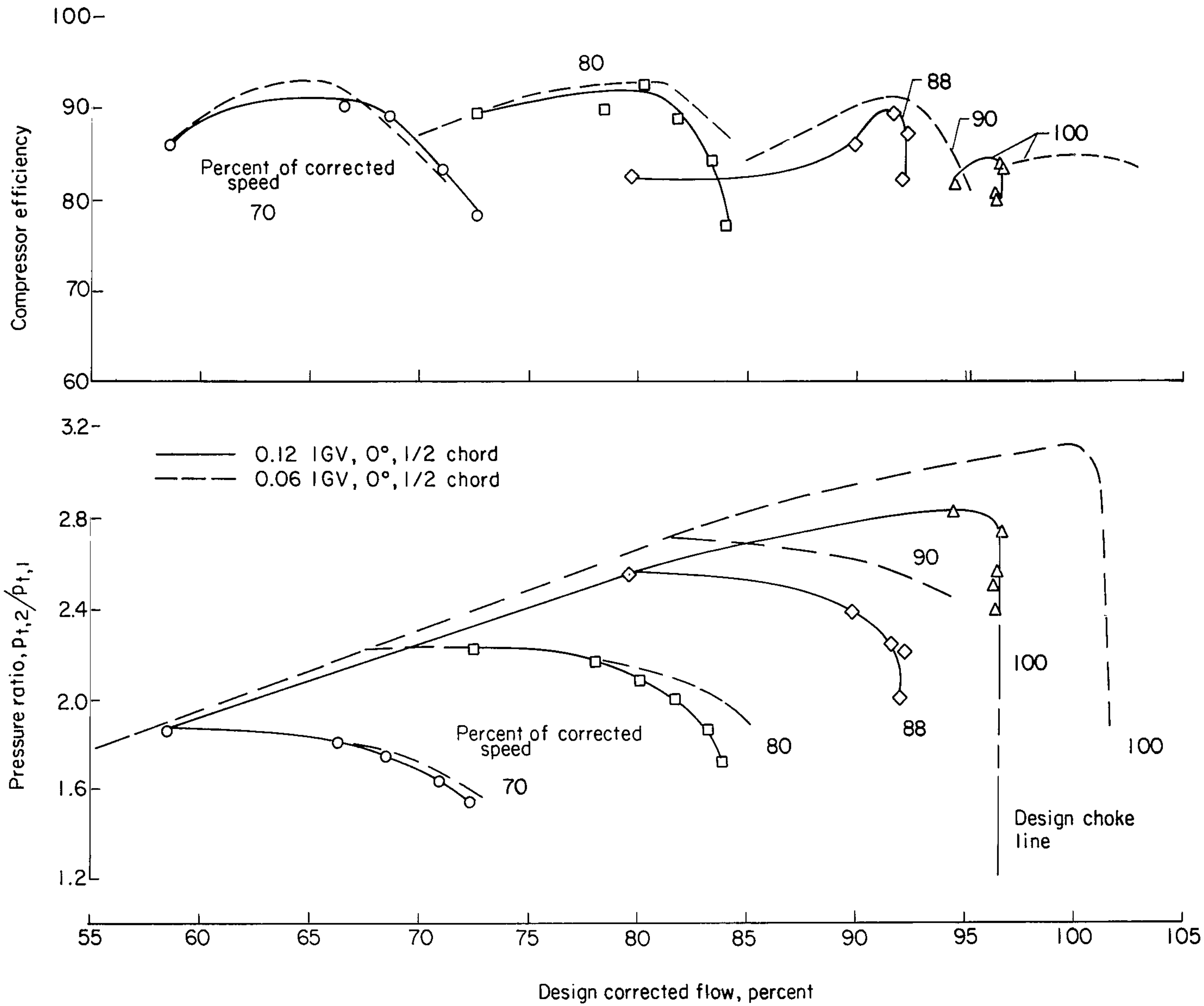


Figure 15.- Effect of inlet-guide-vane thickness on compressor performance.

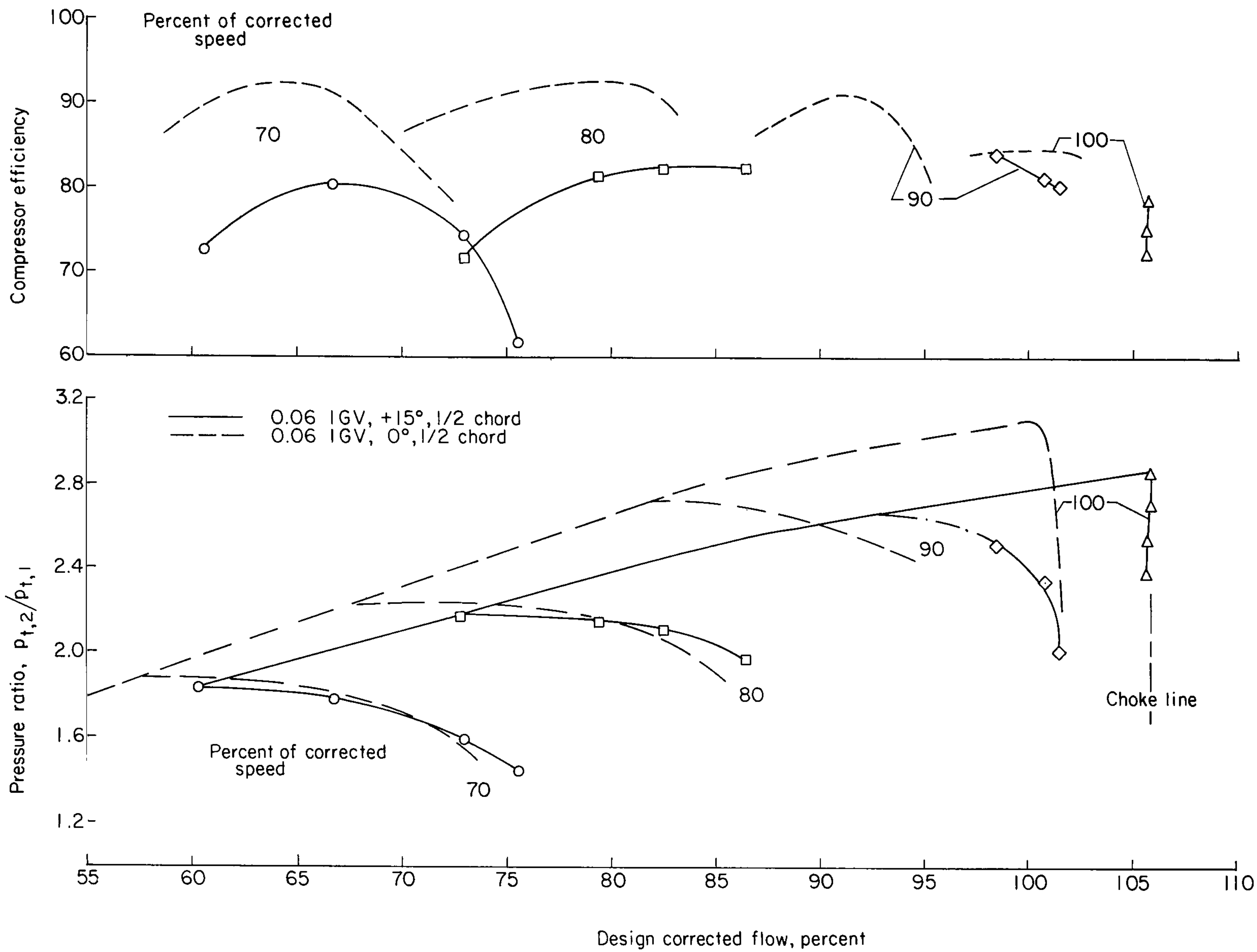


Figure 16.- Effect of inlet-guide-vane angle on compressor performance.

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