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NASA CR114566

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EFFECT OF CROSSFLOW VELOCITY ON VTOL LIFT FAN BLADE PASSING FREQUENCY NOISE GENERATION

by

D.L. STIMPERT

GENERAL ELECTRIC COMPANY

(NASA-CR-114566) EFFECT OF CROSSFLOW VELOCITY ON VTOL LIFT FAN BLADE PASSING FREQUENCY NOISE GENERATION (General Electric Co.) 56 p HC $5.00 CSCL 01C

N73-21928

Unclas

G3/02 69424

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA-Ames Research Center

CONTRACT NA52-5462

D.H. HICKEY - PROJECT MANAGER

56

1. Report No. NASA CR-114566	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Effect of Crossflow Velocity on VTOL Lift Fan Blade Passing Frequency Noise Generation		5. Report Date February 1973
		6. Performing Organization Code
7. Author(s) D. L. Stimpert		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address General Electric Company Aircraft Engine Group Cincinnati, Ohio 45215		11. Contract or Grant No. NAS2-5462
		13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

Analysis of noise measurements taken during tests of a remote lift fan wing installation, a V/STOL model transport with both lift and lift/cruise fans, and XV5B research aircraft flight tests has indicated a definite increase in pure tone sound pressure level due to crossflow over the face of the lift fans. The fan-in-wing and V/STOL model transport tests were conducted in the NASA Ames 40' by 80' (12.2 m x 24.4m) wind tunnel and the XV5B flight tests at Moffett Field. Increases up to 10 dB were observed for the lift fan installations tested at crossflow to fan tip velocity ratios (V_o/V_{tip}) up to 0.25. Cruise fan noise levels were found to be unaffected by the external flow. The noise level increase was shown to be related to an increase in fan distortion levels.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Blade Passing Frequency Crossflow Velocity Lift Fan VTOL	Unclassified - Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	48	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

FOREWORD

The author wishes to acknowledge the cooperation of D. Hickey, J. Kirk, and A. Atencio of NASA Ames in making available the data sources used in the technical analysis of this report.

[redacted]

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SYMBOLS

		Units
P_T	Total pressure	psia (N/M^2)
PNL	Perceived Noise Level	PNdB
PWL	Sound Power Level re 10^{-13} watts	dB
R	Radius or distance from noise source	feet (m)
SPL	Sound Pressure Level re 0.0002 D/cm^2	dB
V_o	Wind tunnel velocity	ft/sec (m/sec)
V_{tip}	Fan tip speed	ft/sec (m/sec)
α	V/STOL model transport yaw angle	degrees
β_v	Exhaust louver angle of V/STOL model lift fans	degrees
γ	Acoustic angle relative to V/STOL model lift/cruise fan inlet axis	degrees
δ_{CN}	V/STOL model cruise nozzle exhaust exit angle	degrees
θ	Acoustic angle relative to V/STOL model lift/cruise fan exhaust axis	degrees
σ_v	Louver rotation angle of V/STOL model lift fans	degrees

SUMMARY

Acoustic data taken from three separate test programs conducted at NASA Ames Research Center were examined to determine the effect of crossflow velocity on the pure tone noise generation of lift fans. An increase of 10 dB in the pure tone power level at a crossflow to fan tip velocity ratio of 0.25 was observed in the remote lift fan installation which was on an LF336/C lift fan mounted in a semi-span model and tested in the NASA Ames 40 ft by 80 ft (12.2 m by 24.4 m) wind tunnel. A second test of a V/STOL model transport -- also in the tunnel -- indicated that cruise fan pure tone noise levels were unaffected by external flow since their inlet axes are aligned with the flow and therefore the fans are not in a crossflow. However, the deep-inlet lift fans in the nose of the V/STOL model were affected by crossflow. A pure tone power level increase of 5 dB was observed at a crossflow to fan tip velocity ratio of 0.25. Actual flight test data from XV5B flyovers at different speeds indicated an increase of 8 dB in the pure tone PWL at a crossflow to fan tip velocity ratio of 0.2.

Pure tone sound power level generation is not only a function of crossflow velocity, but is also affected by fan design, inlet depth, and distortion sensitivity.

INTRODUCTION

Research is currently in progress to define and design V/STOL aircraft which may be used as commercial subsonic transports. Many of the configurations being studied by NASA and the airframe manufacturers incorporate lift fans which are fixed in wing pods or mounted in the fuselage with the inlets oriented vertically. As the aircraft transitions from vertical to horizontal flight, or vice versa, these lift fans experience various degrees of cross-flow over the inlets. This report is concerned with the effect of such cross-flow velocities on the pure tone noise levels of these fans. Noise measurements taken on various configurations of three lift fan system are examined and analyzed to give an empirical understanding of the results. Two of the systems -- the LF336/C Fan-In-Wing and the V/STOL model -- were tested in the NASA Ames 40' by 80' (12.2 m x 24.4 m) wind tunnel. The third system was the XV5B aircraft which was tested in flyover passes at Moffett Field.

ACOUSTIC DATA ACQUISITION AND PROCESSING

LF336/C Fan-In-Wing Test

For these tests, the fan was mounted in a model wing with the major strut parallel to the ground plane as shown in Figure 1. Noise levels were recorded by twelve farfield microphones arranged as shown in Figure 2 and by an acoustic probe in the fan exhaust nearfield. Complete test log sheets, data records, and reduction details for the acoustic probe measurements plus a brief description of the overall LF336 test program are given in Reference 1. The data from the farfield microphones were recorded on magnetic tape which was then processed by NASA Ames through a six percent Bruel and Kjaer filter and the output displayed on strip charts. These data were not corrected for tunnel reverberation effects.

V/STOL Model Transport Test

For this series of tests, Figure 3 identifies the fan locations on the model and the microphone locations in the wind tunnel. Figure 4 is a schematic of the V/STOL model used in these tests. Noise measurements were recorded on magnetic tape at various tunnel speeds for various combinations of fans in operation by NASA Ames personnel. The magnetic tapes were processed at Edwards Flight Test Center to give 1/3 octave band sound pressure levels at each microphone for each test point. All data for this report were referenced to a 120 foot radius by extrapolating the SPL's measured at each microphone under the assumption of spherical divergence. As in the previous configuration, no corrections for wind tunnel reverberation effects were included.

XV5B Flight Test

Microphone locations and flight paths at Moffett Field for approach and level flyover passes of the XV5B aircraft are shown in Figure 5. The General Electric Sound Evaluation Unit was used for acoustic data acquisition on the test site and preliminary processing of the data. Final data processing including corrections to standard day conditions (77° F (298° K), 70% relative humidity) was completed by General Electric Company in Evendale.

DISCUSSION

LF336/C Fan-In-Wing Test

During October and November, 1970, the LF336/C lift fan was tested in the 40' by 80' (12.2 m x 24.4 m) wind tunnel at NASA Ames to determine the effect of crossflow on lift fan noise. The LF336/C is a single stage lift fan driven by a tip turbine which accepts the full flow of one dry J85-5 turbojet engine. The configuration and design parameters of the LF336/C fan reported here are as follows:

LF336/C

90 leaned vanes
2 chord spacing
with acoustic splitter
with acoustic frame treatment
no exit louvers
1.3 pressure ratio
36 inch diameter (0.914 m)
950 ft/sec tip speed (290 m/sec)

Figure 6 and 7 indicate an increase in pure tone sound pressure level at each microphone for increasing crossflow (tunnel velocities). In this report, crossflow is expressed as the ratio of tunnel velocity to fan tip velocity. Results are shown for two fan speeds (80% and 88%) and with the possible exception of microphone 11, data from these two speeds reduce to the same curve. From the microphone locations given in Figure 2, microphones 1 and 12 are seen to be at the same acoustic angles as microphones 3 and 10 respectively. However, microphones 1 and 12 being twice as far from the fan should be 6 dB lower than microphones 3 and 10 respectively.

In Figure 7 the data of microphone 12 is 6 dB lower than microphone 10 without crossflow. Microphone 1 data from Figure 6 is not lower than microphone 3 data by 6 dB because of the reverberation in the wind tunnel.

Figure 8 shows the effect of crossflow on pure tone sound pressure levels at the acoustic angle relative to the lift fan inlet axis of microphones

2 through 11. These curves were generated by reading the SPL values of the lines drawn through the data of Figures 6 and 7. Aft quadrant power levels were calculated for each crossflow curve and from these power levels, a curve of power level change as a function of crossflow was generated as shown in Figure 9.

Domas and Kazin (Reference 2) analyzed the near field acoustic probe data from this test and noted that at 87.7% fan speed, there was a 10 to 12 dB increase in pure tone power level at a crossflow velocity of 116.5 knots (59.9 m/sec) (V_o/V_{tip} = 0.236). This point, when spotted on Figure 9, is in good agreement with the power level increase calculated from the farfield microphone data.

In a separate test of the LF336/C at Edwards Flight Test Center, power levels were calculated using acoustic data measured on a 150 foot arc (45.7 m). Reference 3 summarizes the results in which the aft quadrant power levels at 80 and 95% design speed were 139.3 and 136.9 dB respectively. This was an outdoor test with no crossflow effects. From Figure 8, the farfield aft quadrant pure tone power level from the wind tunnel test is 139.9 dB which agrees well with the Edwards Flight Test Center results.

Figure 9 confirms an earlier analysis of the LF336/C Fan-In-Wing Test as presented in Reference 4. The 6 percent pure tone SPL increase with crossflow was seen to be 10 dB at V_o/V_{tip} = 0.2 and 3 dB at V_o/V_{tip} = 0.1.

V/STOL Model Transport Test (Lift Fans)

A second source of information was the test of a scale model aircraft configured as a V/STOL transport in the 40' by 80' (12.2 m x 24.4 m) wind tunnel at NASA Ames. The aircraft had four X376B fans - two deep inlet lift fans in the nose and two tail mounted lift/cruise fans whose exhaust could be vectored downward simulating a lift mode. Exhaust from a T58 gas generator drove the tip turbine of each 36 inch (0.914 m) diameter fan which had a design pressure ratio of 1.08 and a tip speed of 640 feet per second (195 m/sec).

Results of noise measurements taken with lift fans 1 and 2 operating at 3600 rpm are shown in Figures 10 and 11. Each microphone shows an increase in the 1/3 octave band pure tone sound pressure level with increasing tunnel flow or crosswind. Acoustic angles for each microphone were calculated relative to number one fan inlet axis as the fan is oriented in the model (see Figure 4). Figure 12 shows the zero crossflow data replotted as a function of acoustic angle. There are two apparent directivity patterns corresponding to the downstream and upstream microphones. The reason for this is not totally clear at this time; however, it may be that the downstream microphones are shielded from the noise of lift unit number two. The lower levels of the downstream microphones tend to confirm this.

Another approach to understanding the differences between the upstream and downstream microphones is shown in Figure 13. In this figure, the difference between the pure tone SPL with crossflow and the pure tone SPL without crossflow at a given microphone has been plotted versus the corresponding crossflow velocity ratio. It is apparent that the upstream microphones show considerably more scatter than the downstream microphones. The empirical curve through the downstream microphone data is shown on the upstream microphone data. Inspection reveals that microphones 7, 10, and 11 indicate no change or even a slight decrease in pure tone SPL with increasing crossflow (see also Figure 11). If one considers these three microphones circumspect - especially microphone number 7 - then the upstream microphones at least follow the trend indicated by the downstream microphones. With crossflow, the sound waves propagating upstream against the flow may be dispersed more than those propagating downstream. Shielding effects may also be present. Since the change in SPL with increasing crossflow appears to be the same for all acoustic angles of the downstream microphones, this curve can also be considered to be the pure tone power level increase with increasing crossflow for a deep inlet fan. This result will be compared with the results of the LF336/C farfield data later in the discussion.

V/STOL Model Transport Test (Lift/Cruise Fans)

Other tests of the V/STOL model transport were conducted with lift/cruise fans 3 and 4 in operation (at 3600 rpm). The cruise nozzles were vectored at angles (δ_{CN}) of 23°, 56°, 90°, and 138°. For reference, $\delta_{CN} = 0°$ simulates cruise mode with exhaust downstream while $\delta_{CN} = 90°$ simulates a lift mode with the exhaust vectored downward. Figures 14 through 21 show the effect of increased tunnel velocity on the 1/3 octave band pure tone sound pressure level at each microphone at constant cruise nozzle setting. There is, in general, little change in pure tone sound pressure level with increased tunnel velocity. This is not unexpected since the inlet axes of the lift/cruise fans are aligned with the tunnel flow and therefore the fans do not experience crossflow.

The pure tone noise level measured by a given microphone does vary with cruise nozzle angle setting. In Figure 22, for zero tunnel velocity, the downstream microphones show a decrease in noise level as δ_{CN} varies from 23° to 138°. In Figure 23, the upstream microphones indicate an increase in noise level as δ_{CN} varies from 23° to 138°. This indicates some directivity effect is being measured in the tunnel. Since Figures 14 to 20 have indicated little change in pure tone noise level with tunnel velocity, the apparent directivity variations of Figures 22 and 23 with zero tunnel flow may also be considered typical of cases with tunnel flow.

The directivity change in pure tone noise level at each microphone as δ_{CN} varies from 23° to 138° may be explained by the following model. One can extrapolate the curves of Figures 22 and 23 to $\delta_{CN} = 0°$ and obtain a cruise mode directivity pattern. Extrapolation is unfortunately necessary since noise measurements are unavailable for runs with $\delta_{CN} = 0°$. Figure 24 shows the measured zero tunnel flow directivity pattern along with estimated inlet, exhaust, and total directivities. The estimated lines were obtained in the following manner. In the cruise mode with $\delta_{CN} = 0°$, the fan inlet axis and the fan exhaust axis coincide. However, when the cruise nozzle is vectored, the two axes no longer coincide. This means that a given microphone "sees" an acoustic angle relative to the fan exhaust axis that is different from the acoustic angle relative to the fan inlet axis. The total SPL at a given microphone is the sum of the inlet radiated SPL at an acoustic angle relative to the inlet axis and an exhaust radiated SPL at an acoustic angle relative to the vectored exhaust axis. Table 1 lists the acoustic angles at each microphone calculated relative to the exhaust axis for each cruise nozzle setting. Since the fan inlet and fan exhaust axes are coincident at $\delta_{CN} = 0°$, the acoustic angles for this setting are the same. As the cruise nozzle angle varies, the acoustic angle relative to the inlet remains constant at each microphone.

At a particular microphone, one can arrive at the following set of equations for the five tests (δ_{CN} = 0, 23, 56, 90, 138):

$$SPL_{\gamma_0} + SPL_{\theta_0} = SPL_{total_0} \quad (1)$$

$$SPL_{\gamma_0} + SPL_{\theta_{23}} = SPL_{total_{23}} \quad (2)$$

$$SPL_{\gamma_0} + SPL_{\theta_{56}} = SPL_{total_{56}} \quad (3)$$

$$SPL_{\gamma_0} + SPL_{\theta_{90}} = SPL_{total_{90}} \quad (4)$$

$$SPL_{\gamma_0} + SPL_{\theta_{138}} = SPL_{total_{138}} \quad (5)$$

where SPL_{γ_0} represents the inlet radiated SPL at an acoustic angle γ with a fan inlet axis of 0 degrees and SPL_{θ_n} is the exhaust radiated SPL at an acoustic angle θ and fan exhaust axis vectored to the value shown. Logarithmetic addition is implied by the "+" sign. The total SPL measured at each microphone at each cruise nozzle setting is a known quantity (Figures 22 and 23 for any microphone). There are, however, six unknowns for this set of five equations - the inlet SPL which is constant for all five cruise nozzle settings since its axis does not move and the five exhaust SPL's for each δ_{CN} setting. If one assumes a value for the inlet SPL, then it is possible to solve the five equations to give a directivity for the exhaust SPL. This was done for each microphone. Downstream microphone equations were solved under the assumption that the inlet SPL at $\delta_{CN} = 0°$ was 10 dB lower than the total SPL as read from Figure 22. Upstream microphones were solved under the assumption that the inlet SPL at $\delta_{CN} = 0°$ was 0.4 dB less than the total SPL as read from

Figure 23 (this forced the exhaust SPL at $\delta_{CN} = 0°$ to be 10 dB below the total). The resulting exhaust directivities are shown in Figure 25. From these curves, an exhaust directivity was chosen and superimposed on the data of Figure 24. An inlet SPL directivity which fits the data in accordance with earlier assumptions was added. This model does explain the trends of Figures 22 and 23. For example, consider microphone 1 and the effect of vectoring the cruise nozzle on it. From Table 1, the acoustic angles relative to the exhaust axis are 172°, 165°, 131°, 98°, and 50° corresponding to $\delta_{CN} = 0°$, 23°, 56°, 90°, and 138° respectively. Relative to the inlet axis, the acoustic angle of the microphone is 172°. Total SPL's at each cruise nozzle setting are the sum of an SPL read from the inlet spectrum at 172° and the exhaust spectrum read at angles of 172°, 165°, 131°, 98°, and 50°. But Figure 24 indicates that the exhaust spectrum decreases with decreasing acoustic angle and therefore the total SPL will also decrease. This is the trend noted for the downstream microphones of Figure 22. Similarly the trends of the upstream microphones of Figure 22 may be explained. In these cases the total SPL's as δ_{CN} varies from 0° to 138° are the sum of the inlet spectrum SPL read at a low acoustic angle and exhaust spectrum SPL's read at successively increasing acoustic angles which causes the total SPL's to increase with increasing δ_{CN}.

There is one further point which should be mentioned concerning the above directivity analysis. D.A. Bies (Reference 5) published results of tests to determine the feasibility making noise measurements in the NASA Ames 40' by 20' (12.2 m x 24.4 m) wind tunnel. His data indicate that the tunnel acts as a reverberant room and that in the range of interest SPL's decrease about 3 dB per doubling of distance from the source compared with the free field decay of 6 dB per doubling.

In this present report, all data from the V/STOL model transport test were referenced to 120 feet (36.6 m) using the free field decay of 6 dB per doubling of distance. As long as the data is plotted at each microphone, there is no error in the shape since only a constant correction factor is applied to each data point. However, plots of SPL versus acoustic angle as in Figure 24 must be reexamined in light of Bies' results. In Figure 26, each data point was replotted using Bies' scaling of $10 \log_{10} (R/120)$. The revised data points at higher angles tend to confirm the shape of the exhaust spectrum.

XV5B Flight Test Results

In tests conducted at Moffett Field, in November, 1971, noise measurements were recorded for approach and level flyover passes of the XV5B research aircraft (Reference 6). A V/STOL aircraft, the XV5B was configured with one X353 lift fan in each wing and one X376B pitch fan in the nose. Two horizontal J85 gas generators provided the flow to drive the three lift units. The wing fans which have a design pressure of 1.115, diameter of 62.5 inches (1.59 m), and tip speed of 720 feet per second (219 m/sec) are aerodynamically scaled versions of the X376B lift fan.

Measured and predicted noise levels for the XV5B approaching a hover point along a nominal ten degree glide slope which the deck parallel are given in Figure 27. At hover, the measured and predicted levels agree, but they diverge during approach with larger differences occurring when the aircraft velocity is higher. The large rise in measured data just prior to hover is thought to be due to operational control procedures by the pilot preparing for hover. The prediction technique did not attempt to model this procedure.

Measured noise levels at two microphone locations (Figure 5) and predicted noise levels for 150 foot (45.7) altitude flyovers at 70 knots (36 m/sec) and 48 knots (24.7 m) are compared in Figure 28. Again the predicted levels are lower than measured. Corrections to account for the effects of crossflow as shown in Figure 6 were incorporated in the prediction technique giving better agreement in Figure 29. Although the crossflow correction included the effects of crossflow on jet noise and fan broadband noise in addition to fan pure tone corrections, the pure tone peak to broadband level was such that the pure tone correction was dominant in the perceived noise level calculations.

The XV5B data from Figures 5 and 28 were used to estimate the effect of crossflow on noise level by assuming the difference between measured and predicted levels are due to this effect. Figure 30 shows the resulting curve. It should be noted that the results here represent only a preliminary analysis of the data. A more detailed and extensive analysis of the flight test data should be considered.

Distortion Correlation

There have been three sources analyzed in an attempt to understand the effect of crossflow on lift fan pure tone noise. Results from Figures 9, 13, and 30 are combined for comparison in Figure 31. For this comparison the PNdB change from the XV5B flight tests was assumed to represent a pure tone power level change since pure tone noise dominates the spectrum. In Figure 31, the XV5B flight test and the Ames wind tunnel test of V/STOL model lift fans generate the same shape curve but with different levels. One possible explanation for the level difference is the inlet configurations of the two installations. The X353 wing fans in the XV5B research aircraft have a shallow inlet configuration. In contrast, the nose-mounted lift fans of the V/STOL model (see Figure 9) have a fairly deep inlet configuration and as a result do not seem to be influenced as much by crossflow velocity as do the X353 fans. LF336/C fan-in-wing data indicate a different shape from the other two sources.

An attempt was made to correlate the XV5B flight test curve and the LF336/C fan-in-wing curve by using rotor exit distortion levels since both fans had shallow inlet configurations. Figure 32 compares measured distortion levels of the X353 lift fan (measured during a separate test - Reference 7) and the LF336/C lift fan at fifty percent annulus area. Figures 31 and 32 were combined to give the change in pure tone level as a function of rotor exit distortion in Figure 33. The comparison of the curves from the X353 and LF336/C fans is encouraging. For distortion levels less than 0.8, the results differ at most by 3 dB even with the obvious difference in shape. Other facts which must be considered are as follows:

1. Both fans are operating in shallow inlets.
2. The LF336/C is a 1.3 P/P, 950 ft/sec (290 m/sec) fan while the X353 is a 1.1 P/P, 720 ft/sec (219 m/sec) fan.
3. The X353 fan has a close rotor-stator spacing while the LF336/C has a two chord rotor-stator spacing. Rotor-stator interaction effects and therefore noise levels are greater for close-spaced lift fans.
4. Intuitively, the shape of the XV5B noise level increase is better. One would expect that the noise increase should reach a level where increased distortion has no further effect. In fact, the noise may eventually decrease when the rotor stalls.

CONCLUSIONS AND RECOMMENDATIONS

From the material presented in this report, the following conclusions may be made:

1. There is a definite increase in lift fan pure tone noise levels associated with an increase in crossflow velocity perpendicular to the fan inlet axis.

2. This increase in noise is related to fan design and distortion sensitivity.

3. Shallow inlet fans exhibit a greater pure tone noise level increase than deep inlet fans at a given crossflow to fan tip velocity ratio.

4. Lift/cruise fans whose axes are aligned with the flow do not show an increase in noise level as velocity parallel to the inlet axis increases.

5. Noise measurements in Ames' 40' by 80' (12.2 m x 24.4 m) wind tunnel can provide important information regarding relative levels of noise generated and definition of source power levels.

Based upon the above conclusions and the material of this report, the following recommendations are submitted:

1. Pure tone noise level increases with crossflow should be incorporated into current prediction techniques.

2. Future noise tests in the 40' by 80' (12.2 m x 24.4 m) wind tunnel should have the microphones located to investigate directivity characteristics of the model being tested.

3. Further research should be conducted to determine the effect of fan design, inlet depth, and distortion sensitivity on lift fan pure tone noise levels when operating in a crossflow.

Table I. Acoustic Angles Calculated Relative to V/STOL Model Lift/Cruise Engine Exhaust Axis.

Microphone (Reference Figure 7)	Cruise Exhaust Exit Angle, δ_{CN} 0°	23°	56°	90°	138°
1	172	165	131	98	50
2	167	162	130	98	51
3	157	160	135	104	58
4	150	156	137	108	64
5	114	126	134	124	94
6	29	46	77	107	148
7	18	37	69	101	146
8	12	31	64	97	144
9	10	30	63	96	143
10	10	33	67	100	148
11	16	39	73	106	154

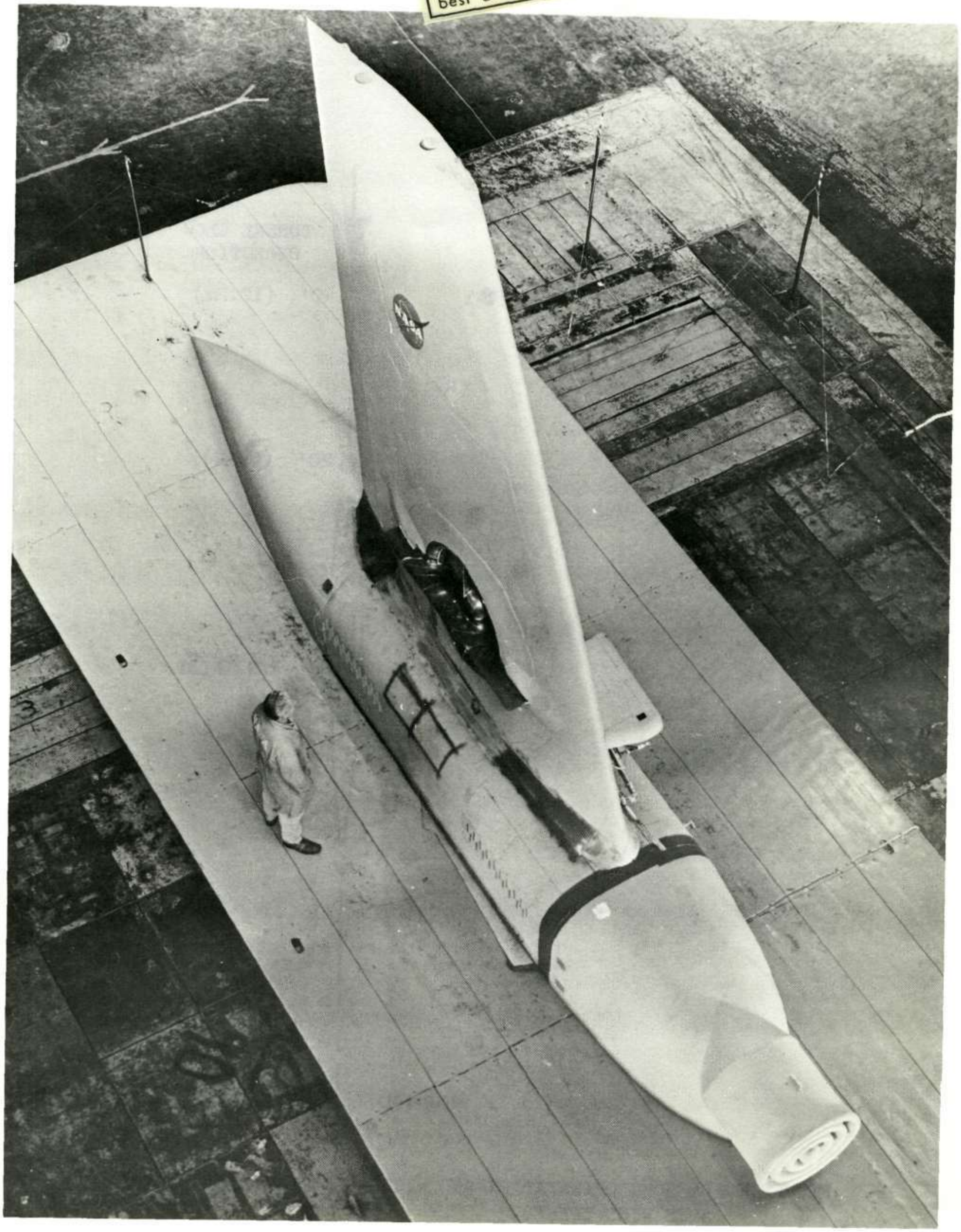


FIGURE 1. LF336/C FAN-IN-WING MODEL IN NASA AMES WIND TUNNEL

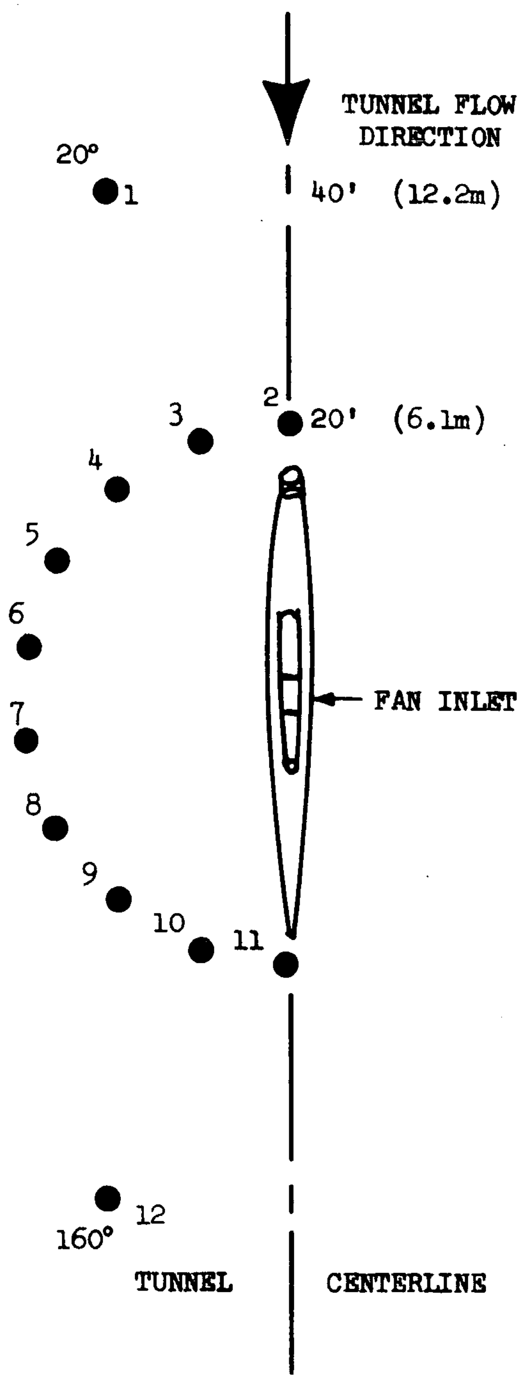


FIGURE 2 LF336/C ORIENTATION AND MICROPHONE LOCATION IN NASA AMES WIND TUNNEL.

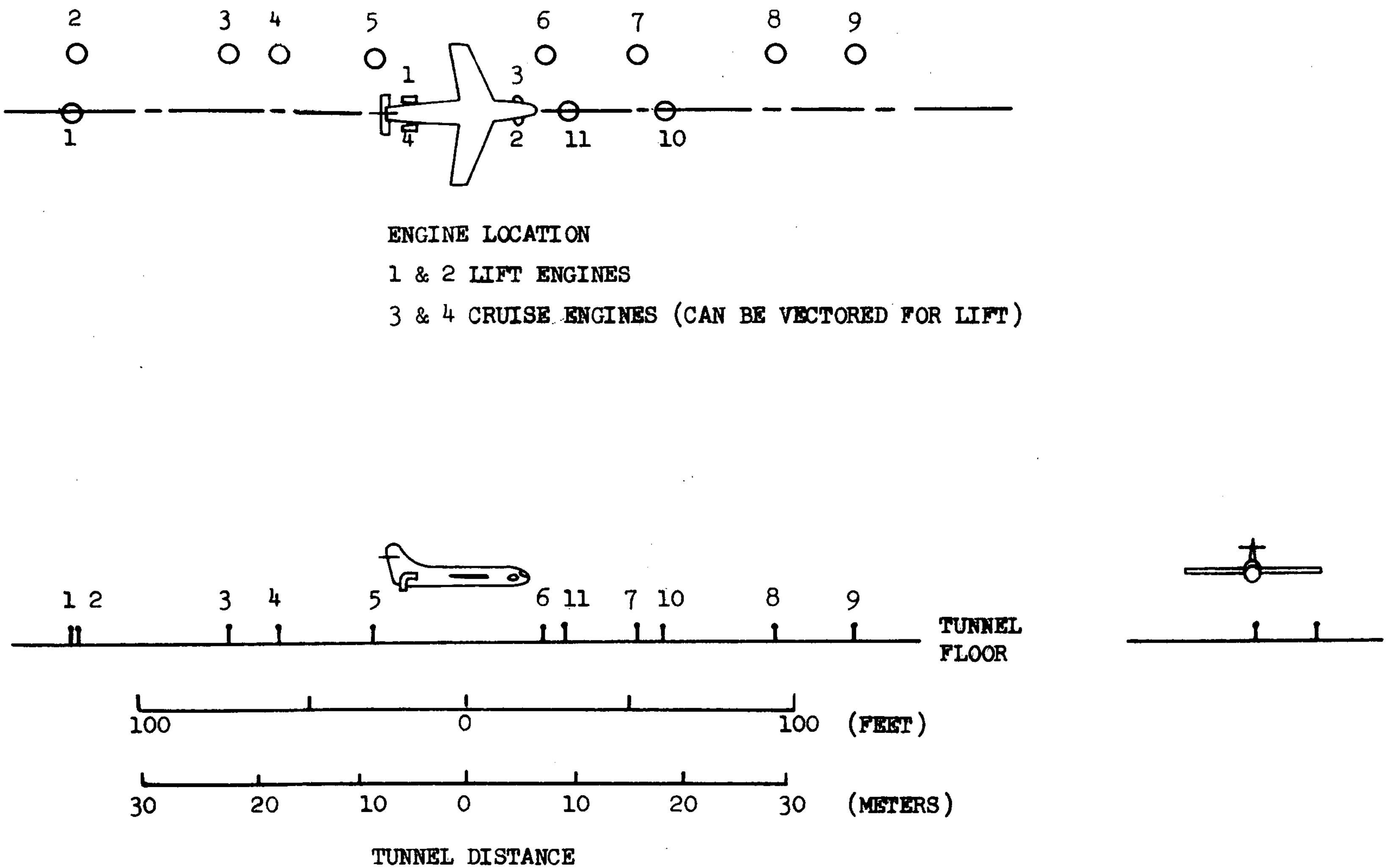


FIGURE 3 MICROPHONE AND V/STOL MODEL TRANSPORT LOCATION IN AMES WIND TUNNEL.

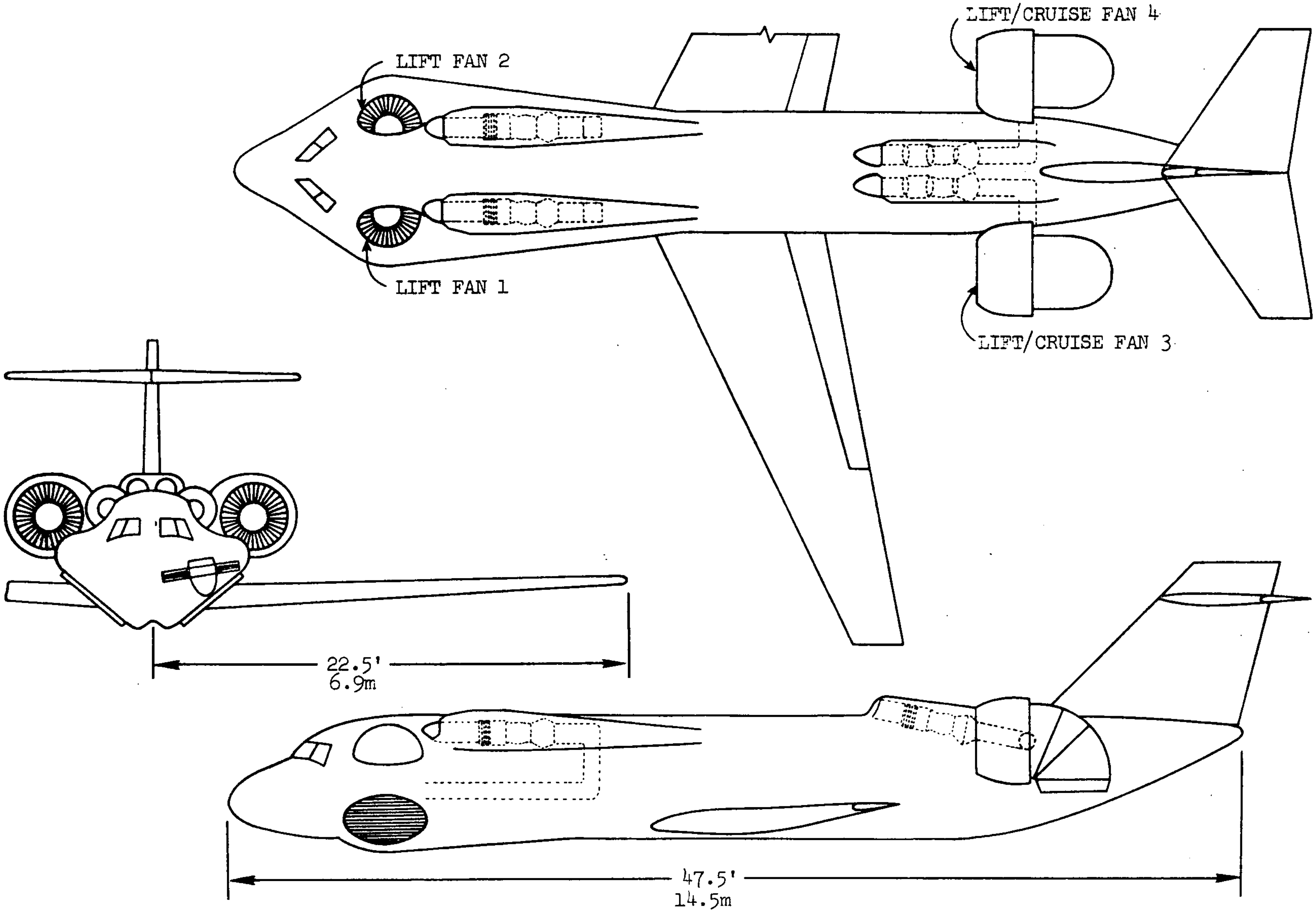
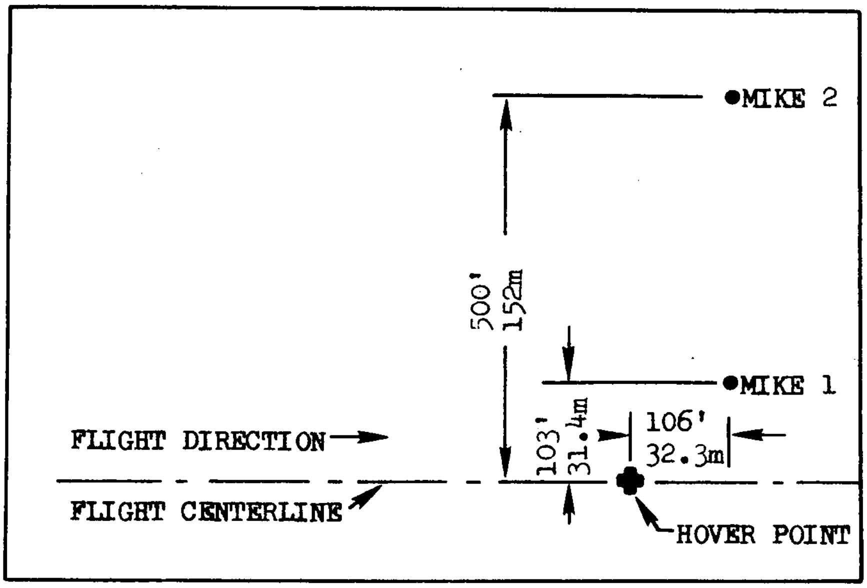


FIGURE 4 V/STOL MODEL TRANSPORT SCHEMATIC

APPROACH PASS MICROPHONE LOCATIONS



150' (45.7m) LEVEL FLYOVER MICROPHONE LOCATIONS

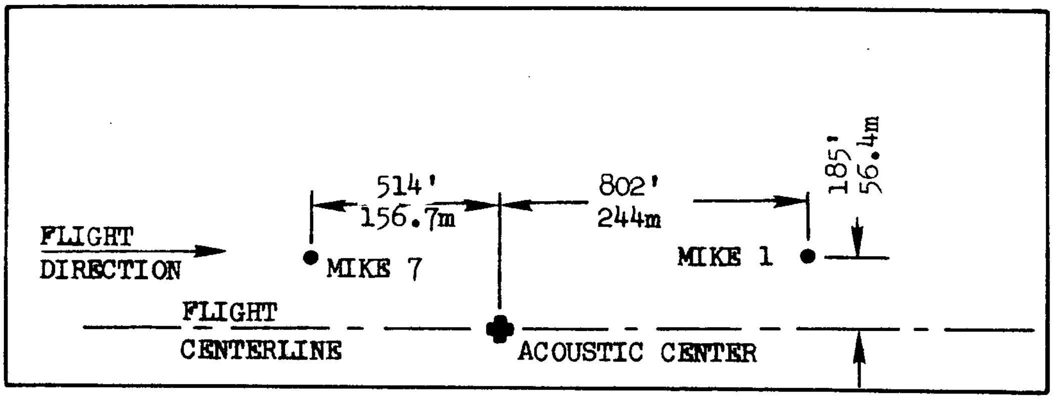


FIGURE 5 MICROPHONE LOCATIONS FOR APPROACH AND LEVEL FLYOVER FLIGHTS OF THE XV5B.

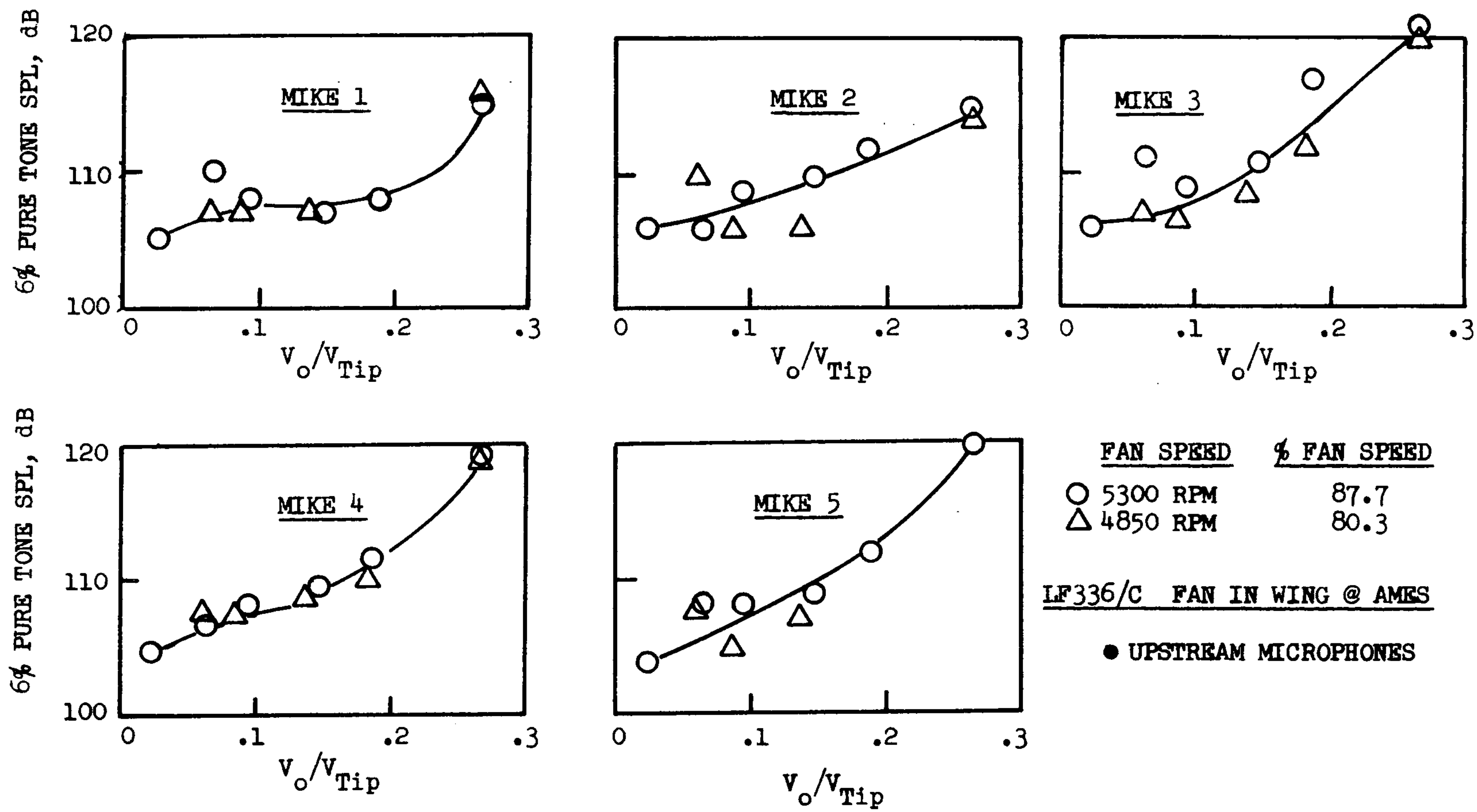


FIGURE 6 EFFECT OF CROSSFLOW ON LF336/C FUNDAMENTAL SPL'S AS MEASURED BY UPSTREAM MICROPHONES.

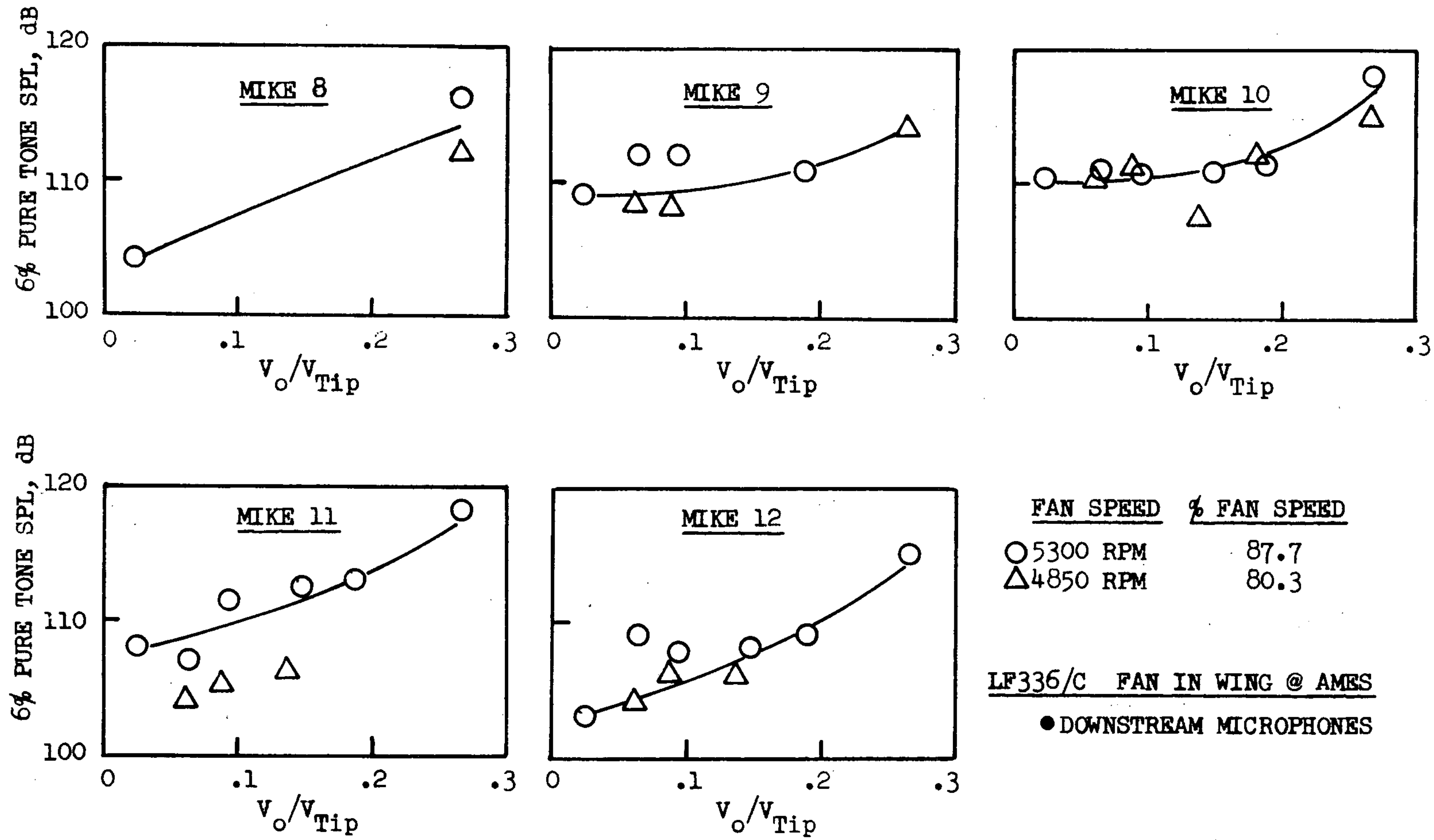


FIGURE 7 EFFECT OF CROSSFLOW ON LF336/C FUNDAMENTAL SPL'S AS MEASURED BY DOWNSTREAM MICROPHONES.

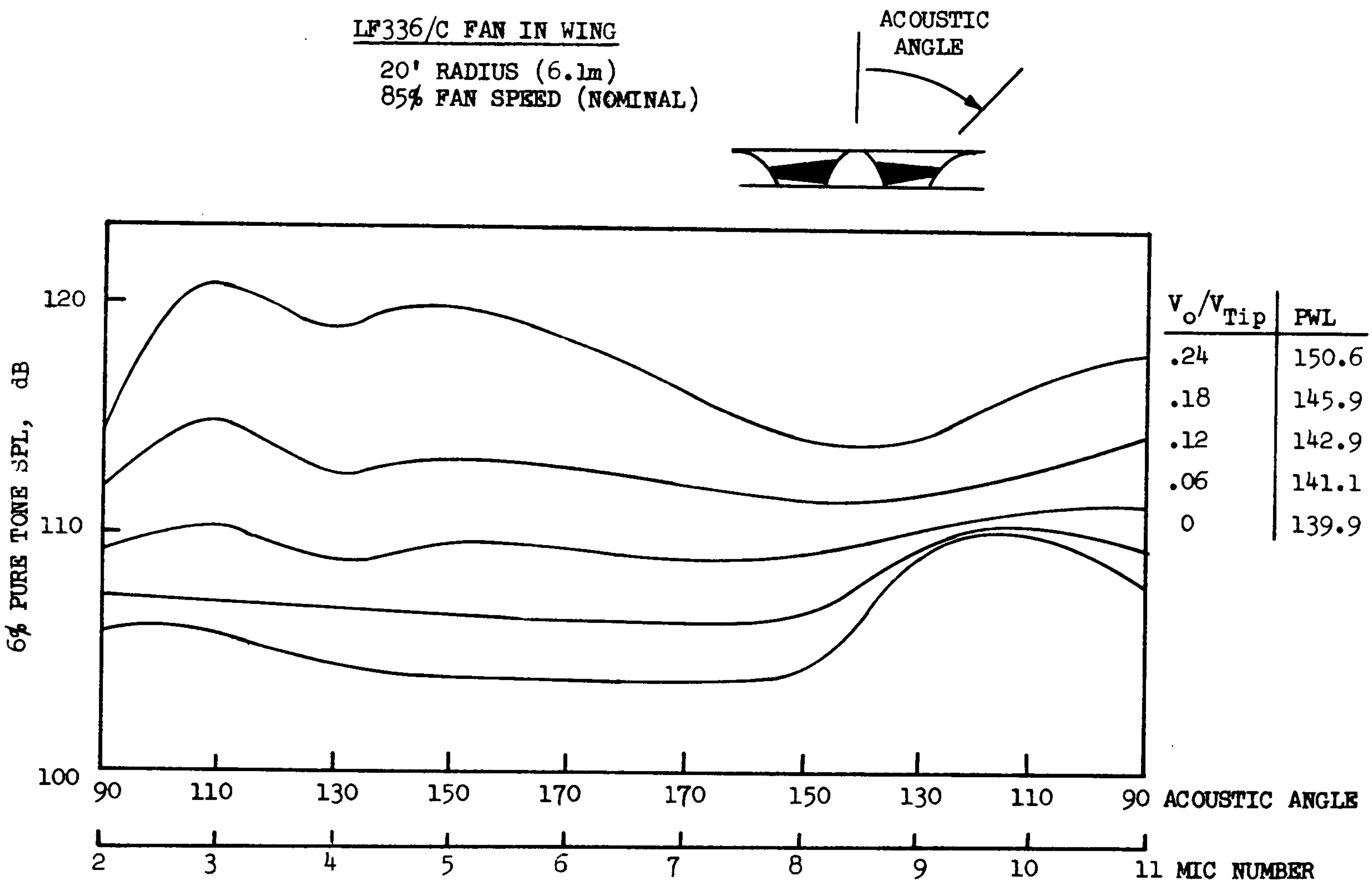


FIGURE 8 EFFECT OF CROSSFLOW ON LF336/C AFT ANGLE DIRECTIVITY PATTERN.

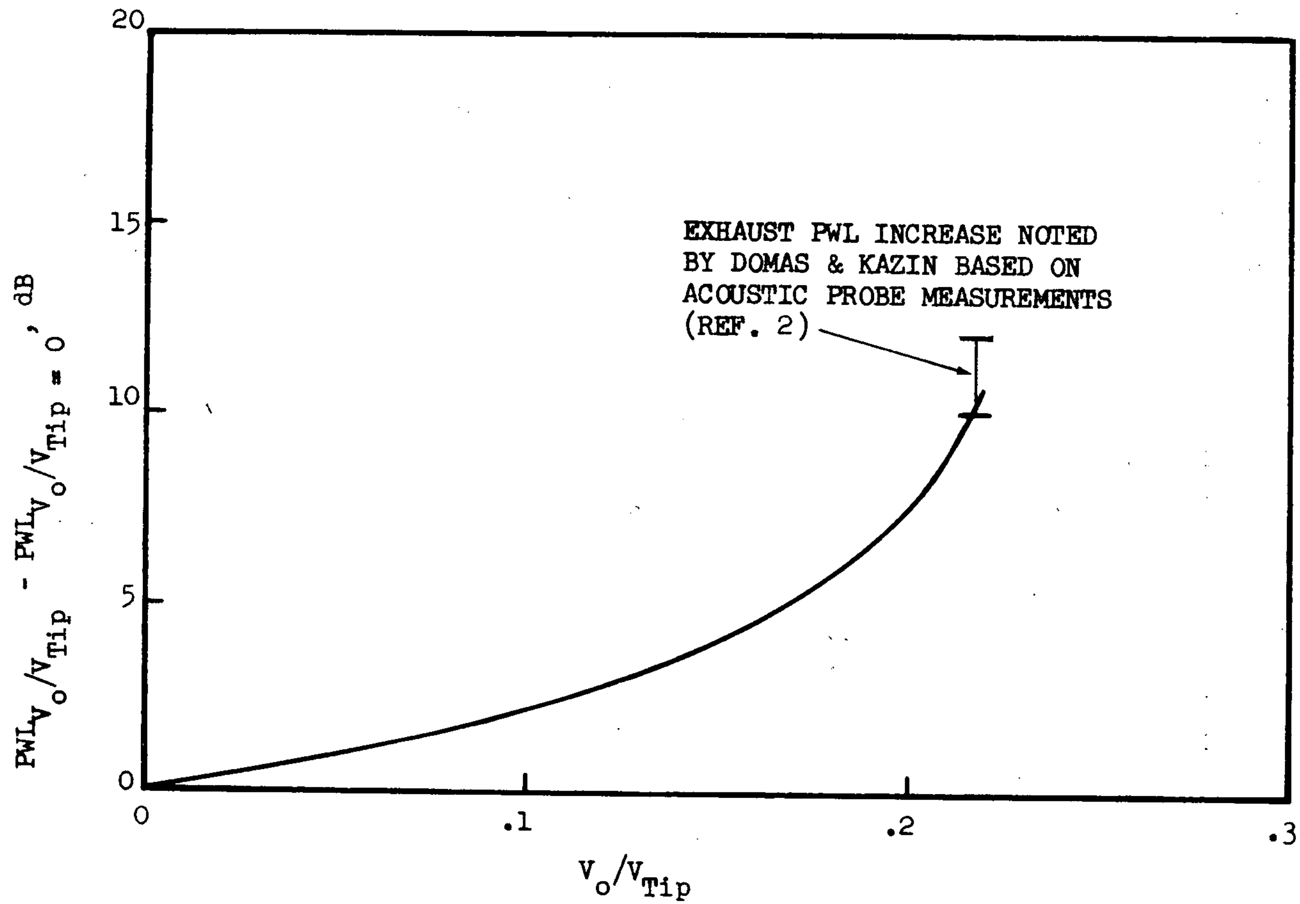


FIGURE 9 AFT QUADRANT POWER LEVEL INCREASE OF THE LF336/C FAN DUE TO CROSSFLOW INCREASE.

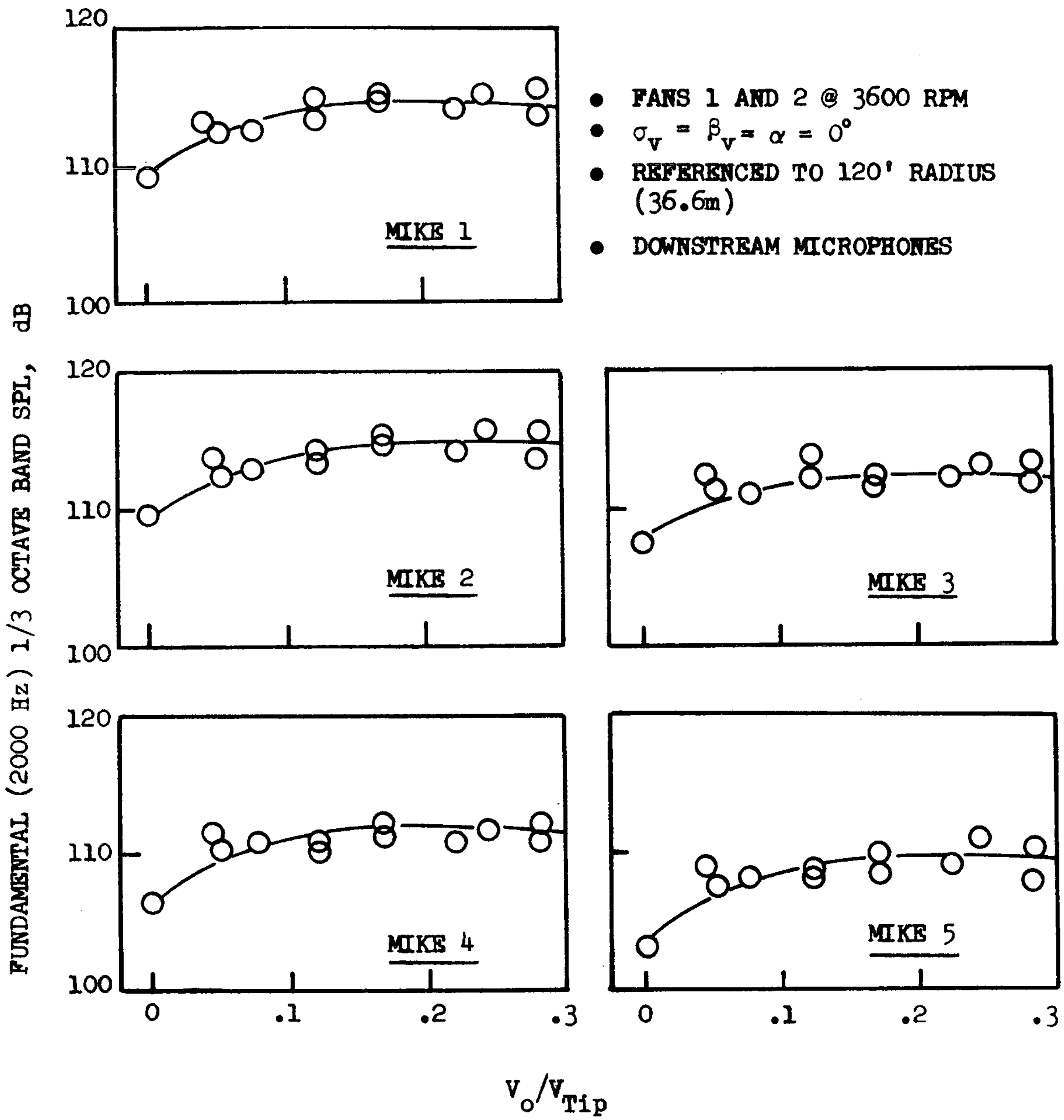


FIGURE 10 EFFECT OF CROSSFLOW ON V/STOL MODEL LIFT FANS MEASURED AT DOWNSTREAM MICROPHONES.

- FANS 1 AND 2 @ 3600 RPM
- $\sigma_v = \beta_v = \alpha = 0°$
- REFERENCED TO 120' RADIUS (36.6m)
- UPSTREAM MICROPHONES

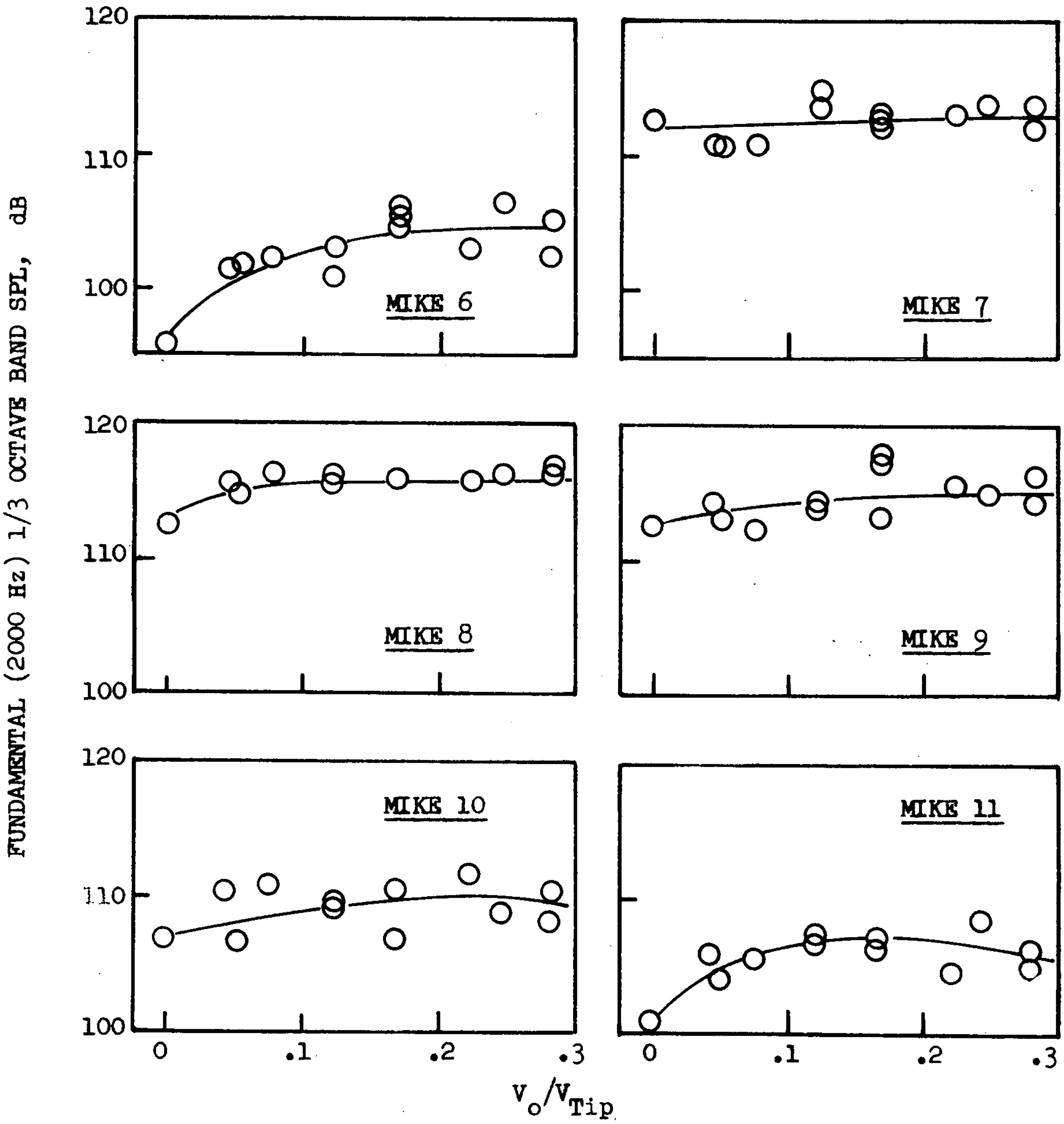


FIGURE 11 EFFECT OF CROSSFLOW ON V/STOL MODEL LIFT FANS MEASURED AT UPSTREAM MICROPHONES.

V/STOL MODEL TRANSPORT IN AMES WIND TUNNEL

- FANS 1 & 2 @ 3600 RPM
- $\sigma_V = \beta_V = \alpha = 0°$
- REFERENCED TO 120' RADIUS (36.6m)
- SOLID SYMBOLS DENOTE DOWNSTREAM MICROPHONES
- ZERO CROSSFLOW

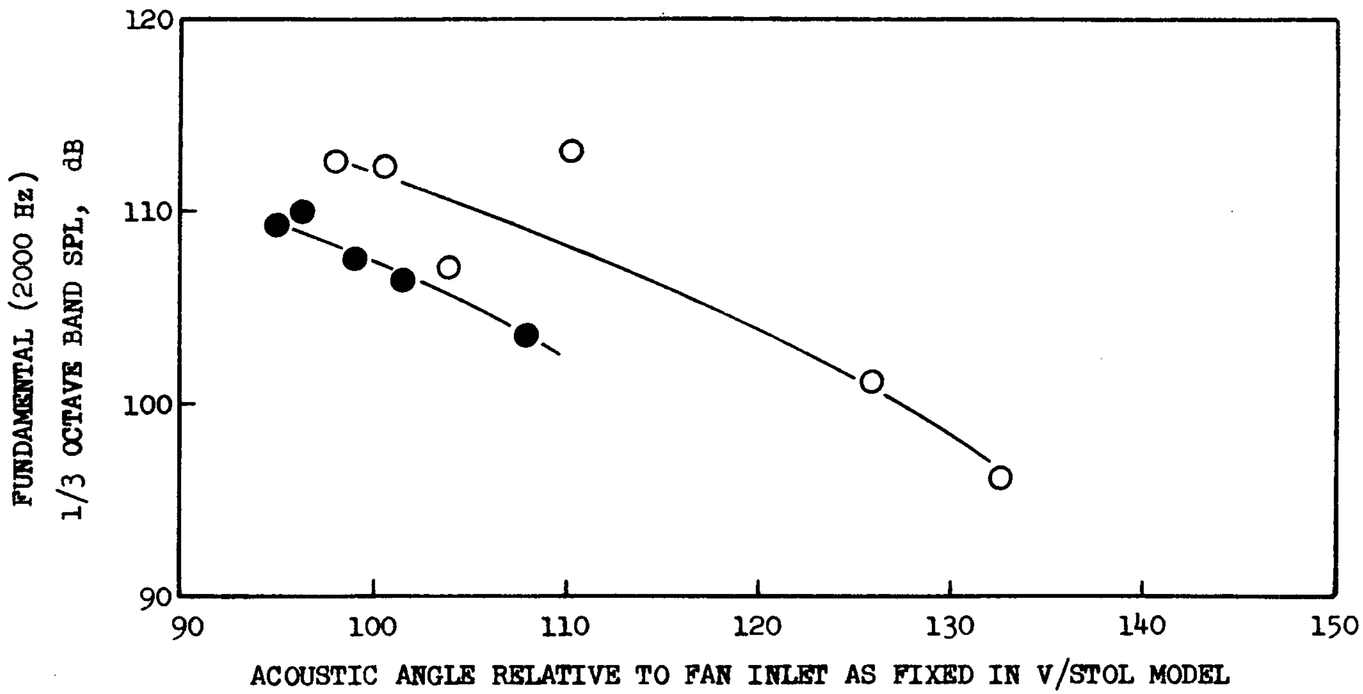


FIGURE 12 DIRECTIVITY PATTERN OF V/STOL MODEL LIFT FANS.

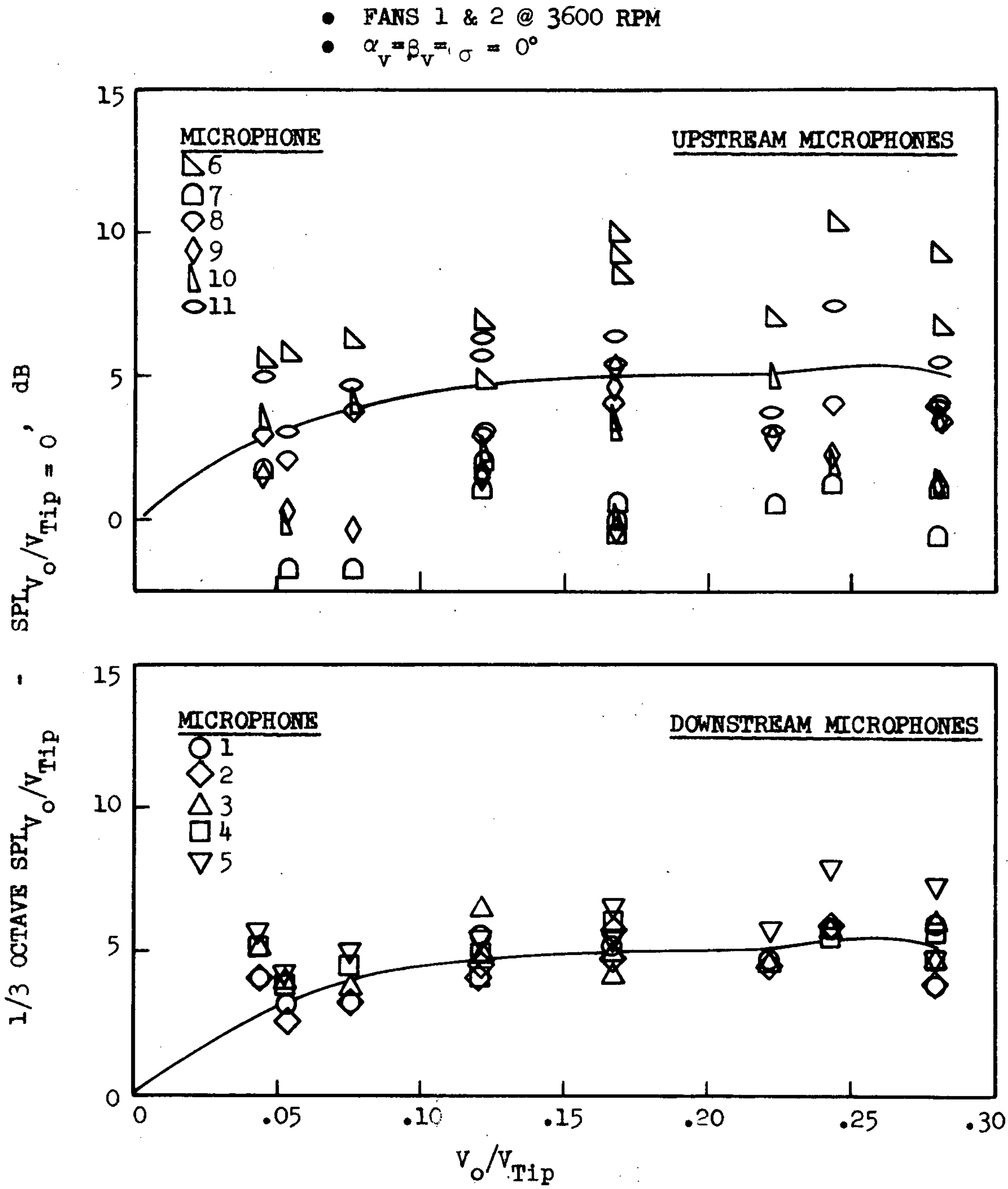


FIGURE 13 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF V/STOL MODEL LIFT FANS.

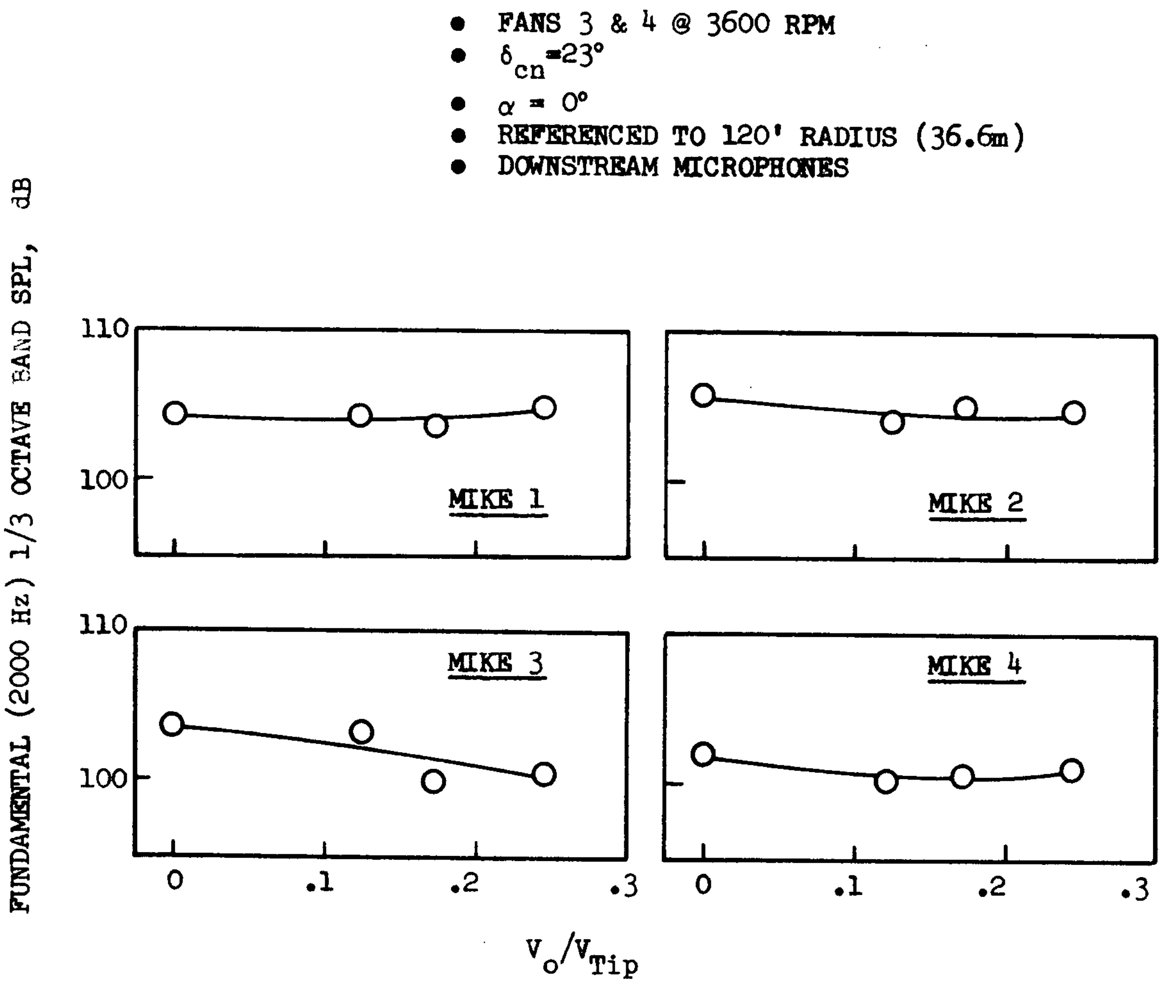


FIGURE 14 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 23°, DOWNSTREAM MICROPHONES.

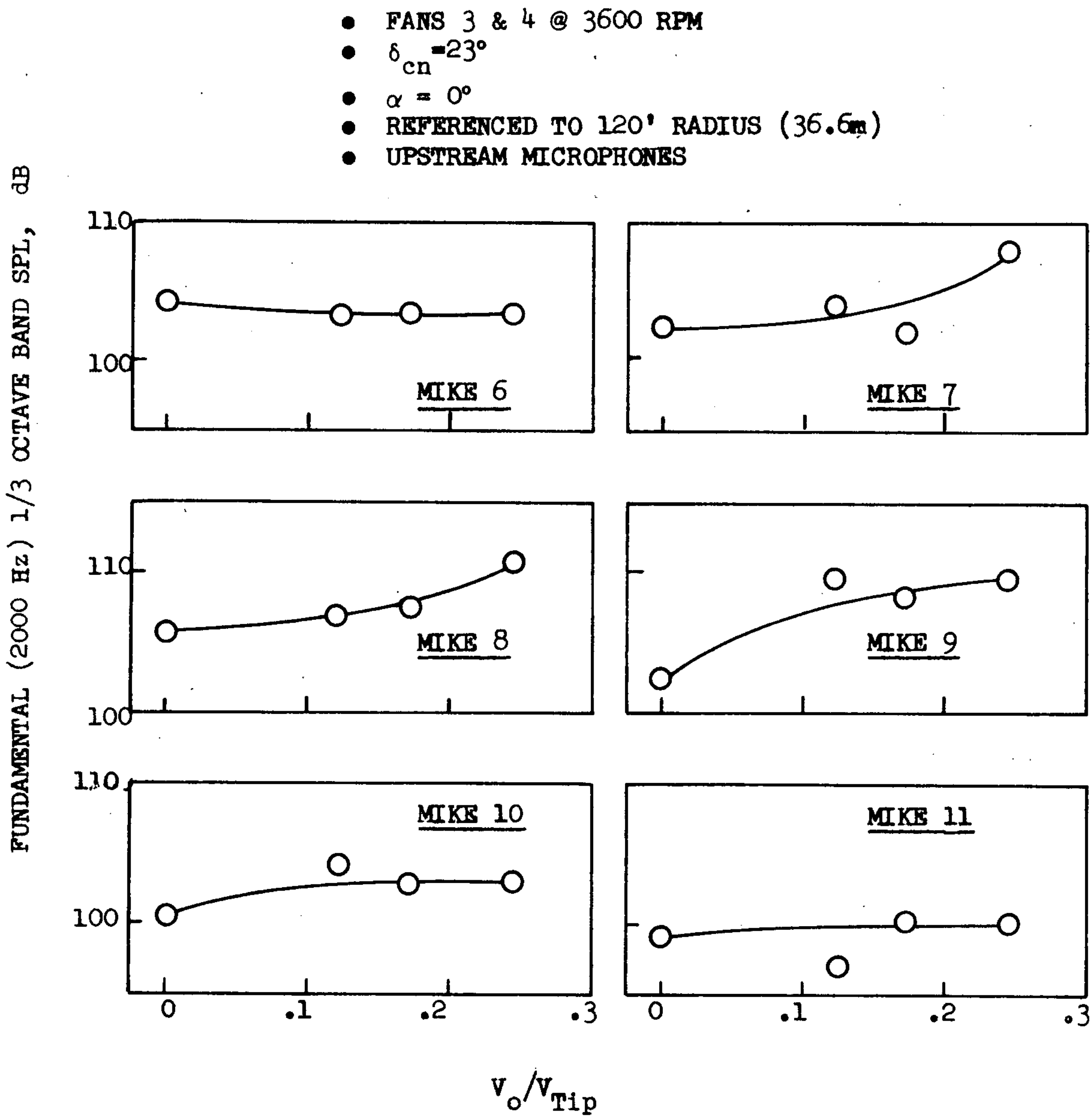


FIGURE 15 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 23°, UPSTREAM MICROPHONES.

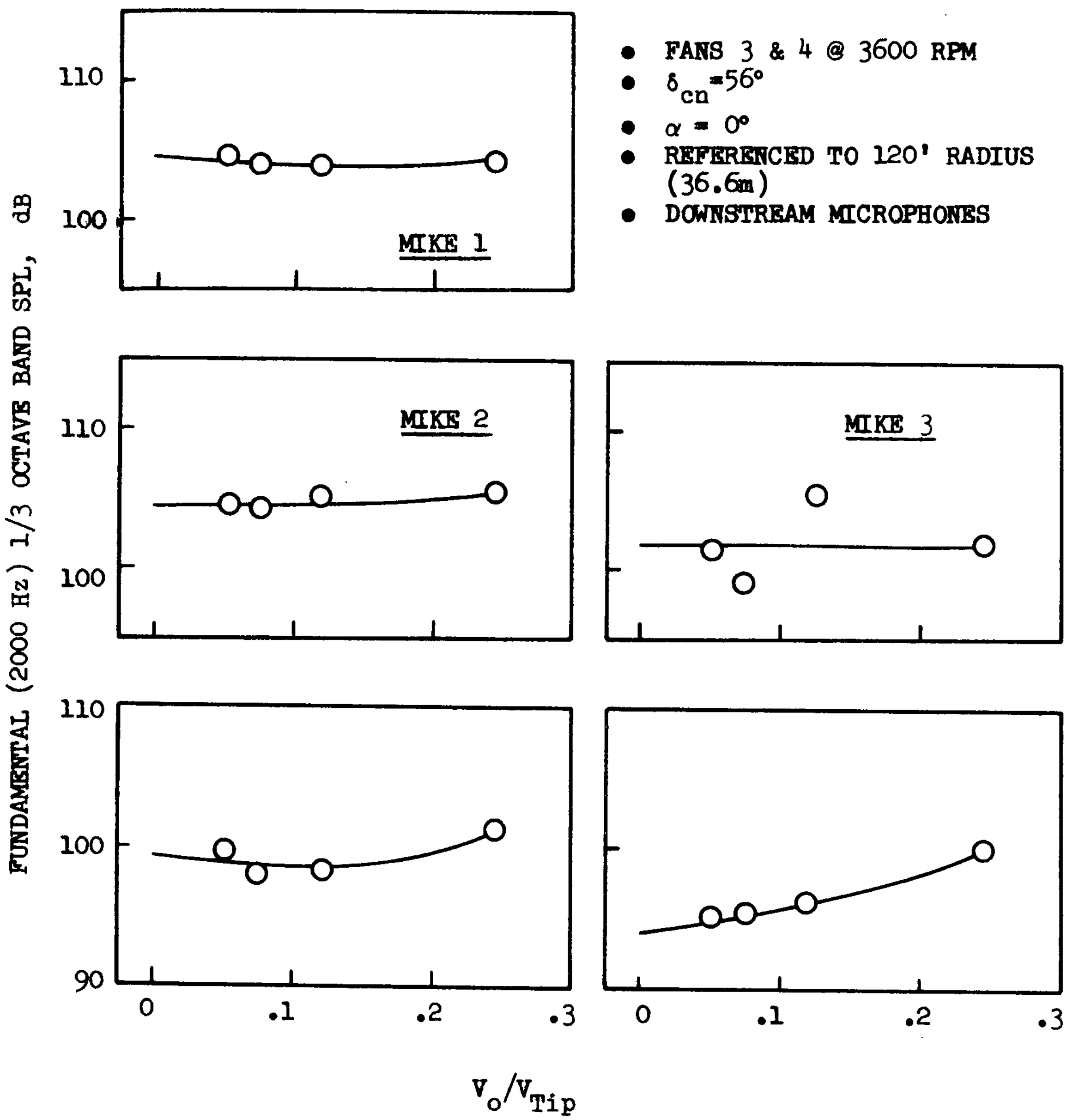


FIGURE 16 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 56°, DOWNSTREAM MICROPHONES.

- FANS 3 & 4 @ 3600 RPM
- δ_{cn}=56°
- α = 0°
- REFERENCED TO 120' RADIUS (36.6m)
- UPSTREAM MICROPHONES

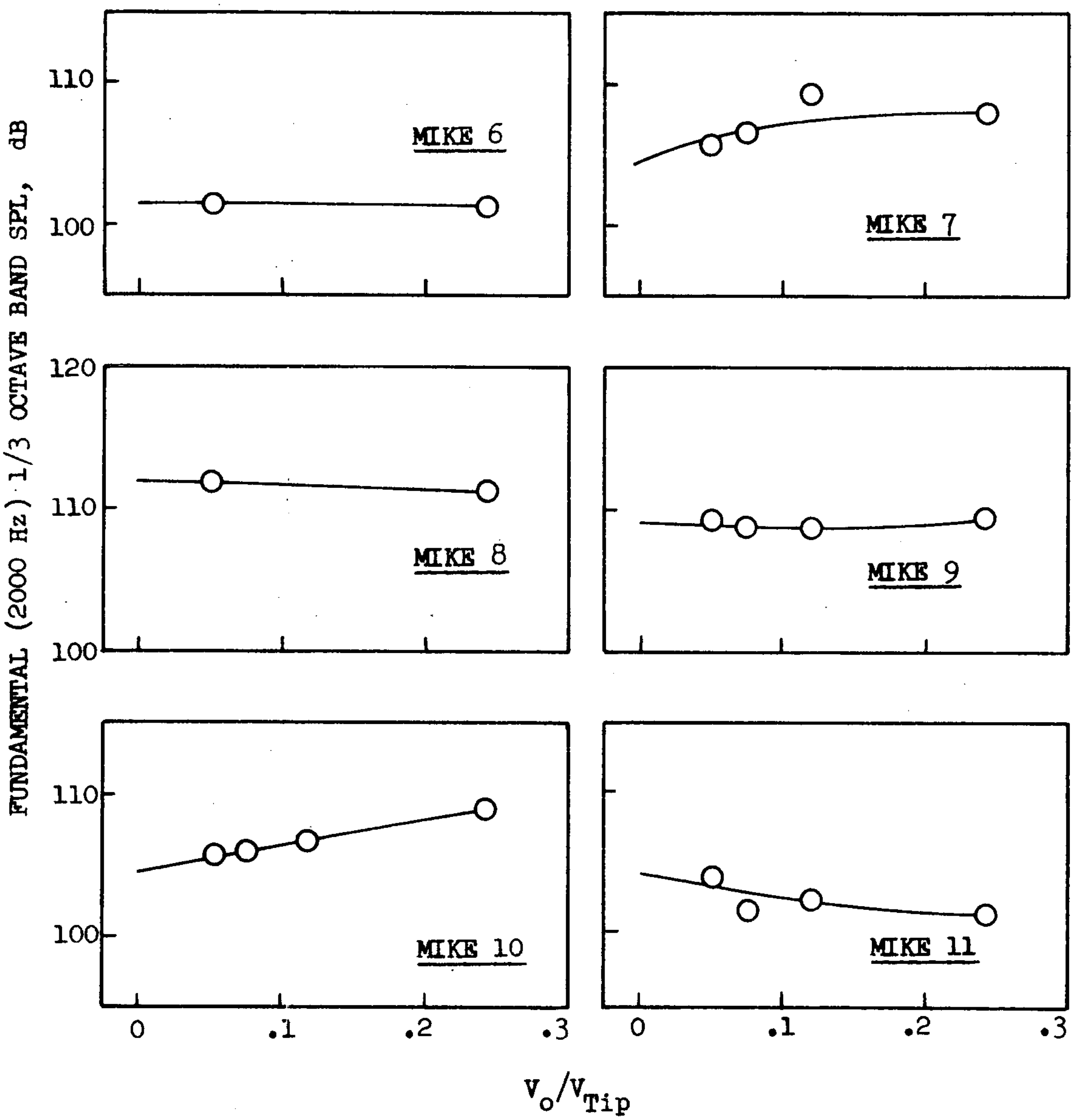


FIGURE 17 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 56°, UPSTREAM MICROPHONES.

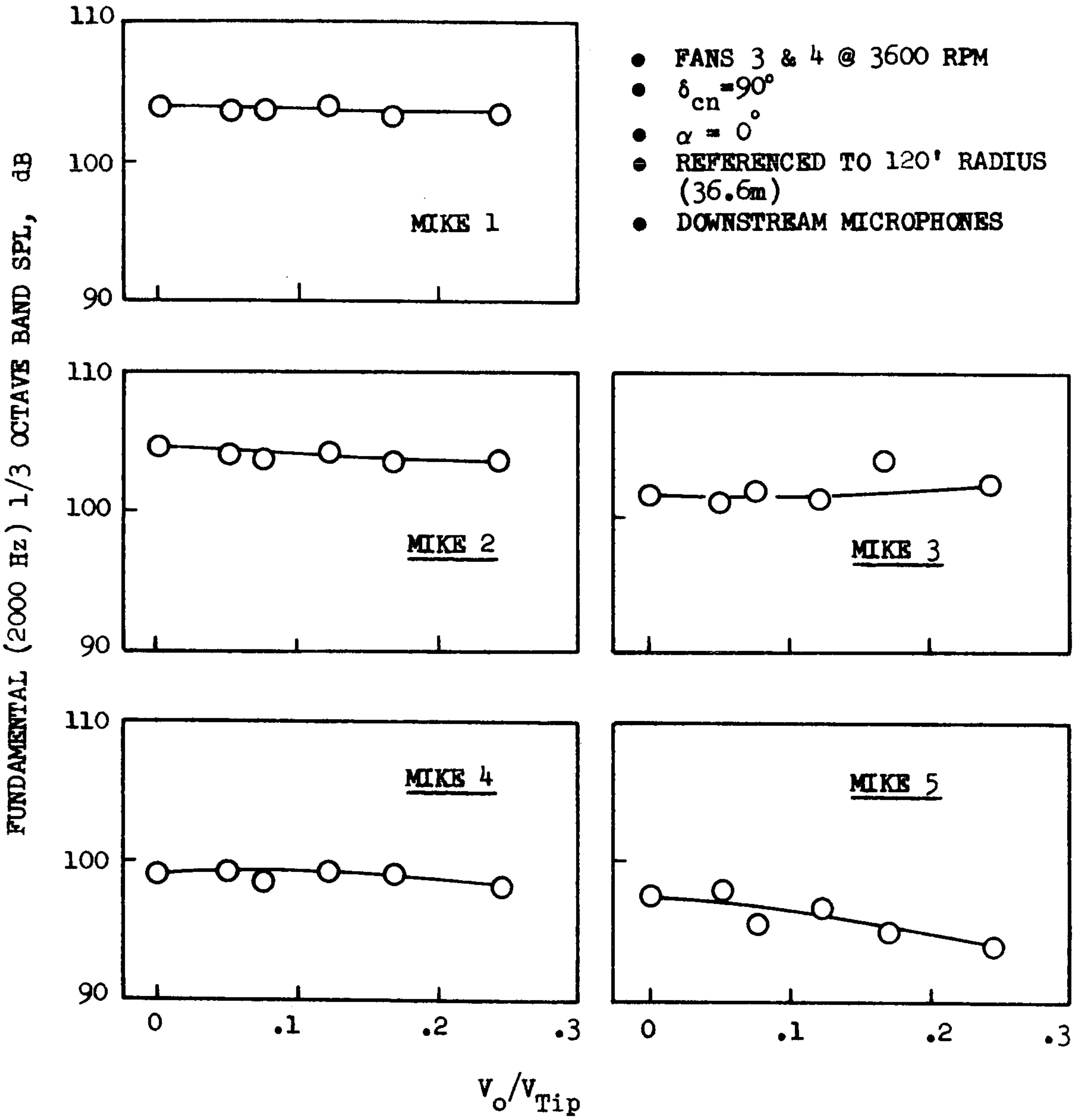


FIGURE 18 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 90°, DOWNSTREAM MICROPHONES.

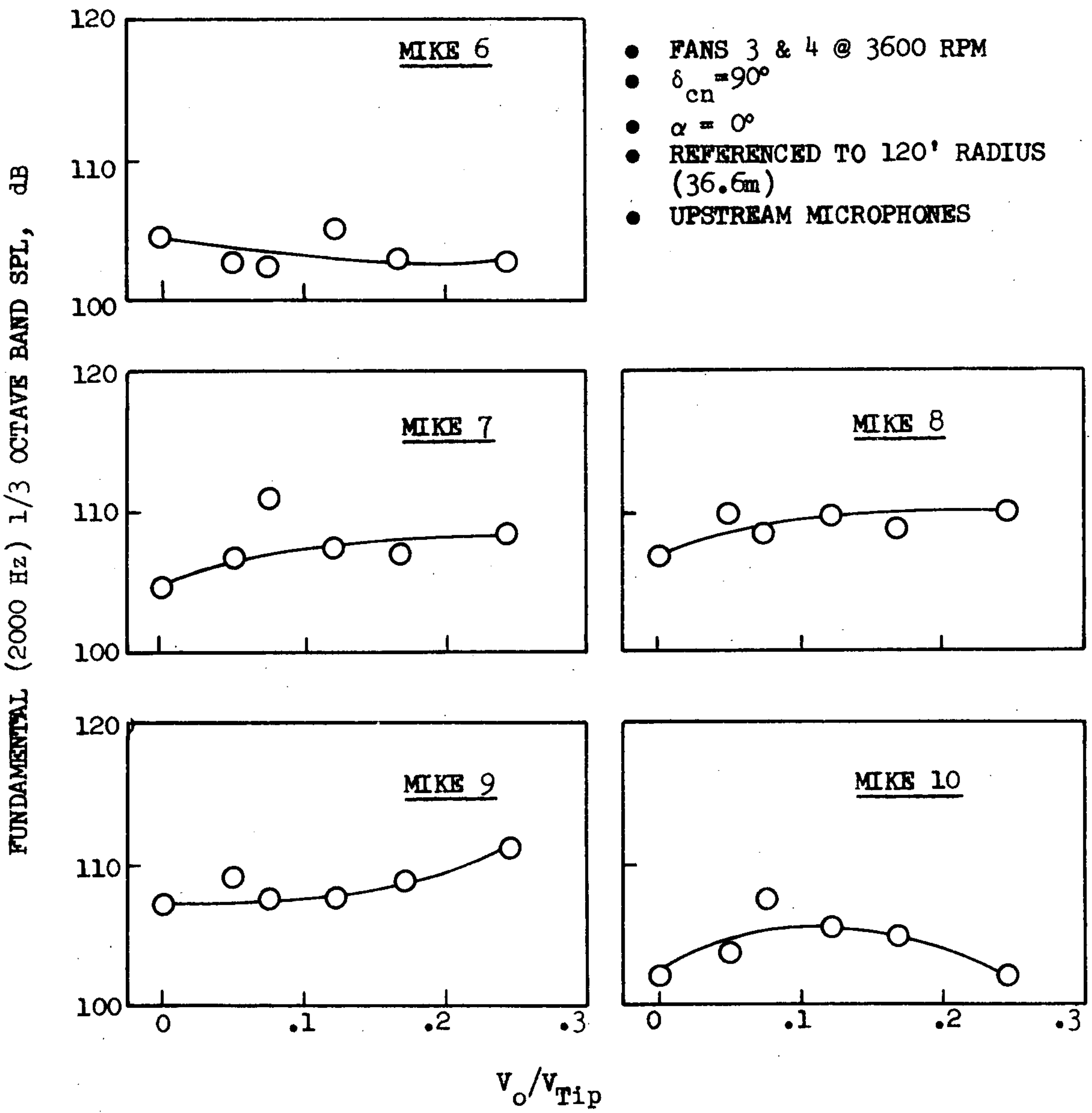


FIGURE 19 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 138°, UPSTREAM MICROPHONES.

- FANS 3 & 4 @ 3600 RPM
- δ_{cn}=138°
- α = 0°
- REFERENCED TO 120' RADIUS (36.6m)
- DOWNSTREAM MICROPHONES

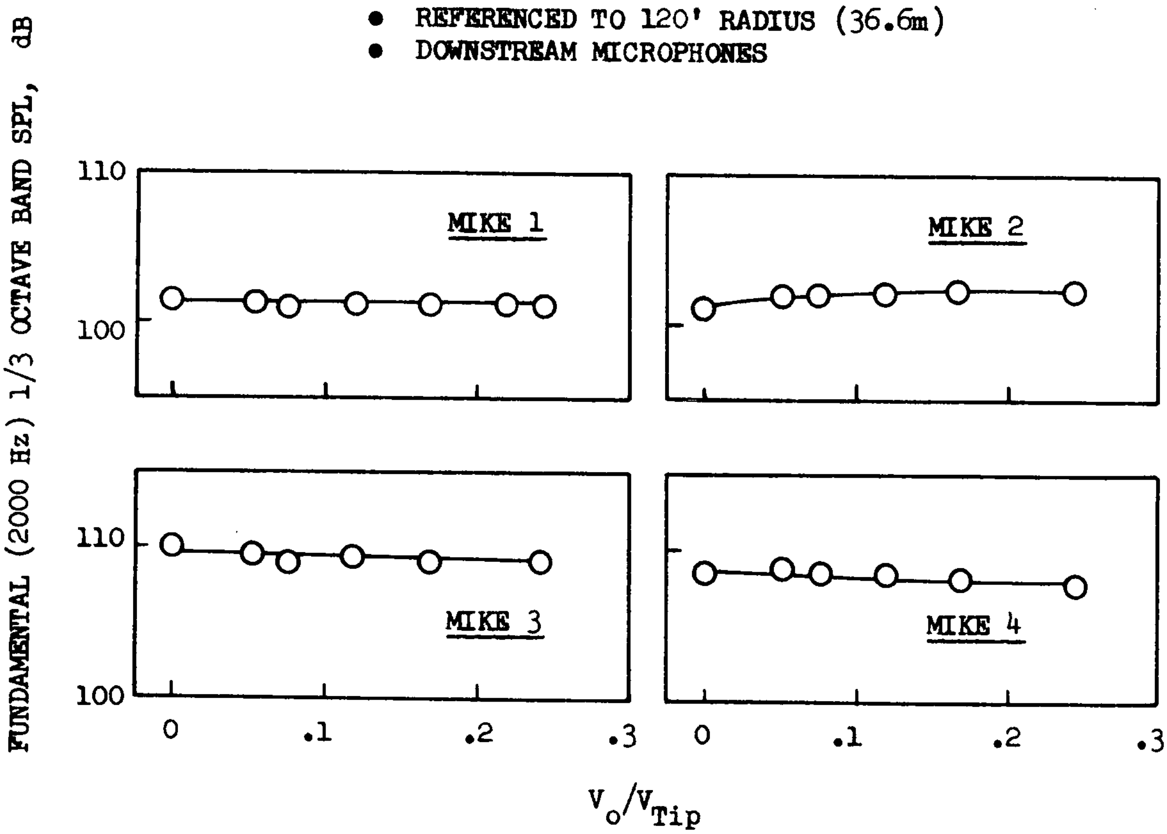


FIGURE 20 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 138°, DOWNSTREAM MICROPHONES.

- FANS 3 & 4 @ 3600 RPM
- δ_{cn}=138°
- α = 0°
- REFERENCED TO 120' RADIUS (36.6m)
- UPSTREAM MICROPHONES

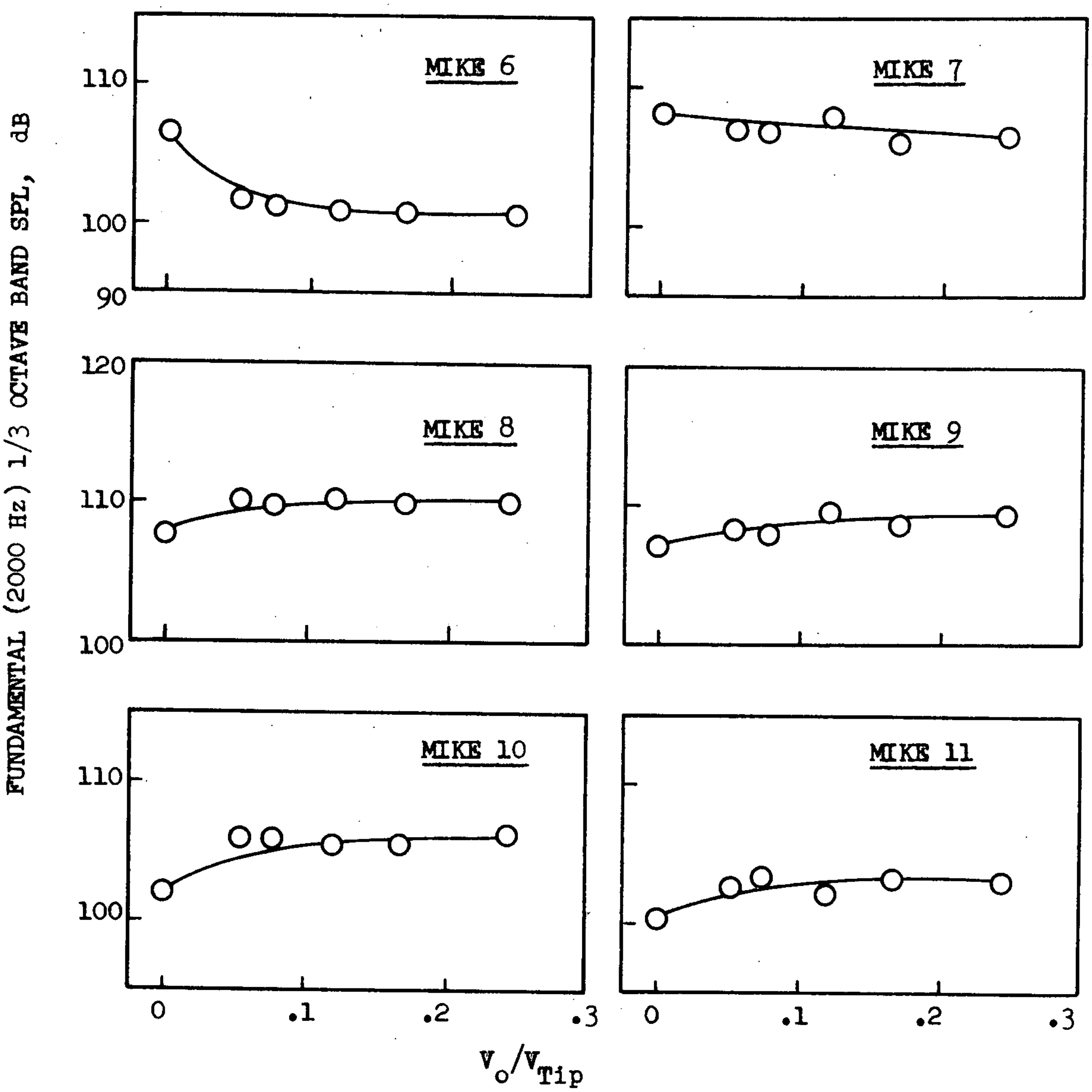


FIGURE 21 EFFECT OF CROSSFLOW ON FUNDAMENTAL SPL OF LIFT/CRUISE FANS AT CRUISE NOZZLE EXHAUST AXIS ANGLE OF 138°, UPSTREAM MICROPHONES.

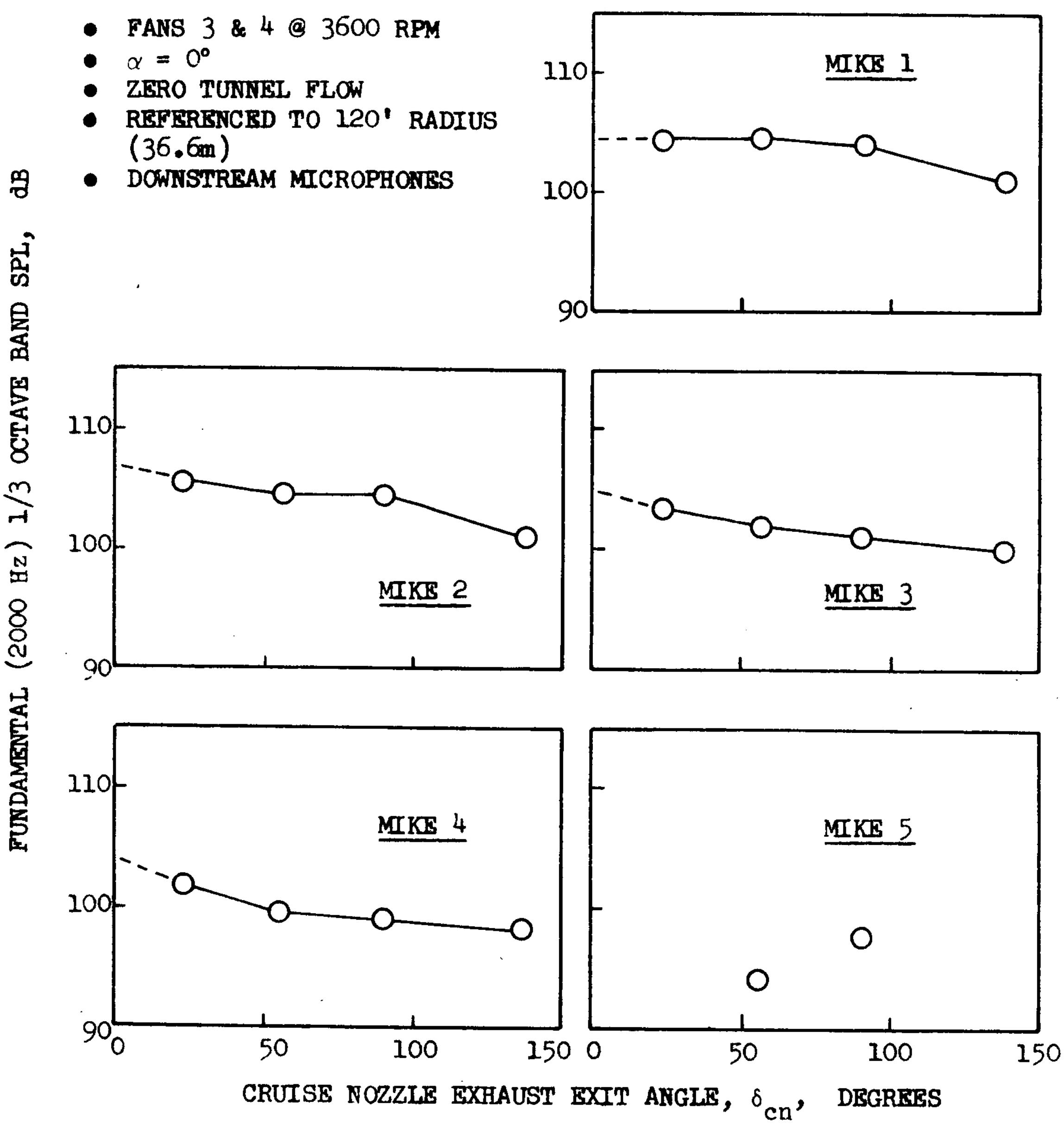


FIGURE 22 EFFECT OF CRUISE NOZZLE VECTORING ON LIFT/CRUISE FAN FUNDAMENTAL SPL AT DOWNSTREAM MICROPHONES.

- FANS 3 & 4 @ 3600 RPM
- $\alpha = 0°$
- ZERO TUNNEL FLOW
- REFERENCED TO 120' RADIUS (36.6m)
- UPSTREAM MICROPHONES

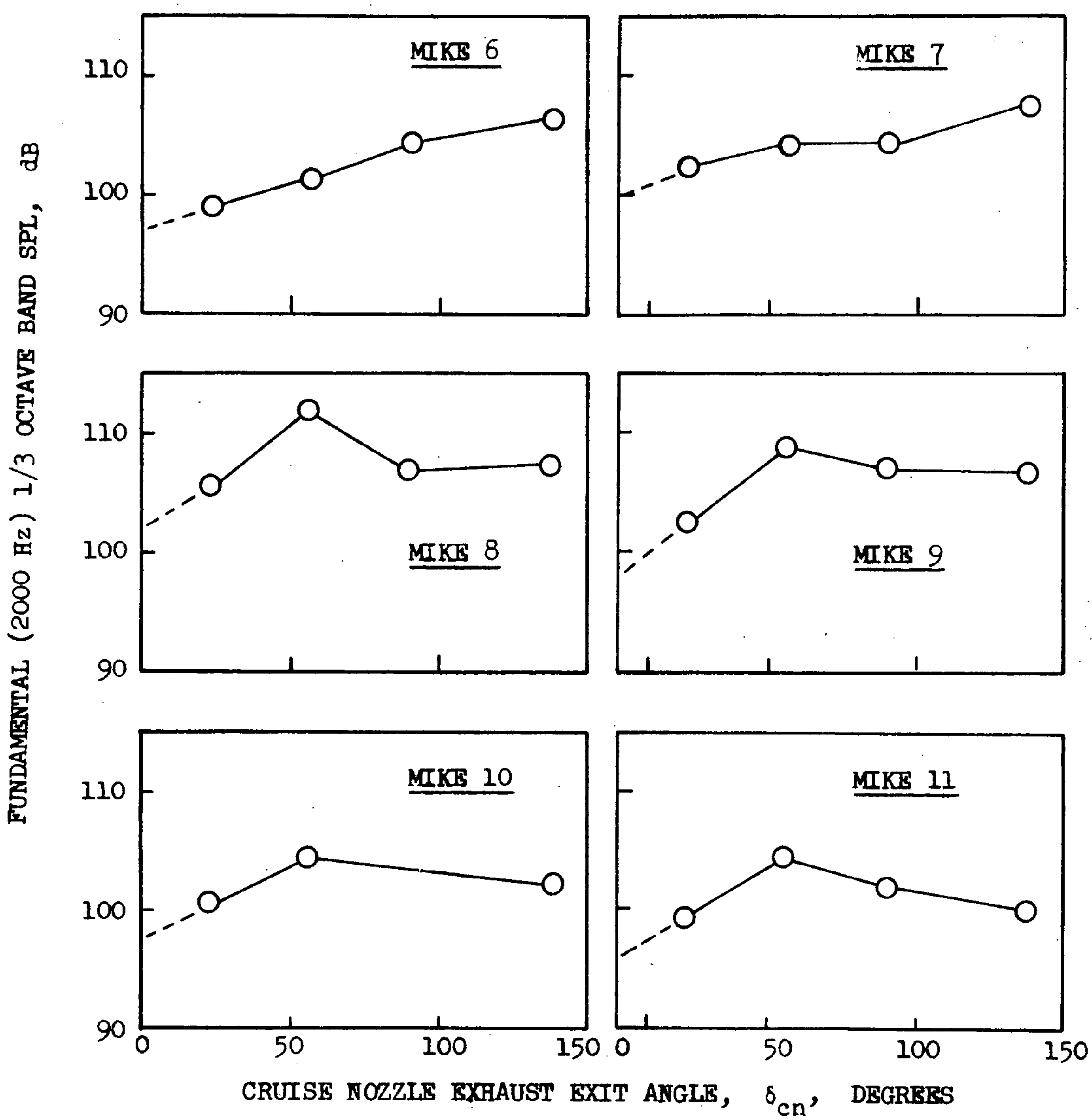


FIGURE 23 EFFECT OF CRUISE NOZZLE VECTORING ON LIFT/CRUISE FAN FUNDAMENTAL SPL AT UPSTREAM MICROPHONES.

- FANS 3 & 4 @3600 RPM
- REFERENCED TO 120' RADIUS (36.6m)
- $\delta_{cn}=0°$ (EXTRAPOLATED DATA)
- SOLID SYMBOLS DENOTE DOWNSTREAM MICROPHONES

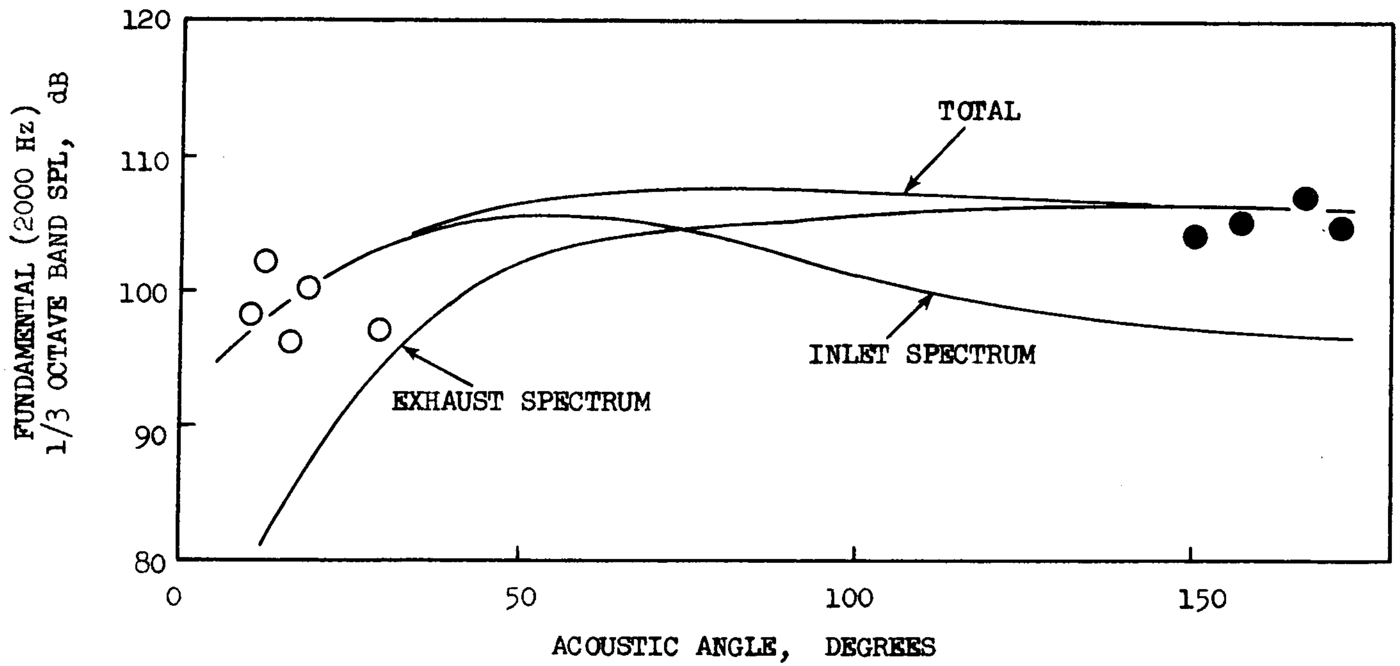


FIGURE 24 DIRECTIVITY PATTERN OF V/STOL MODEL LIFT/CRUISE FANS.

- FANS 3 & 4 @ 3600 RPM
- REFERENCED TO 120' RADIUS (36.6m)
- ZERO TUNNEL FLOW

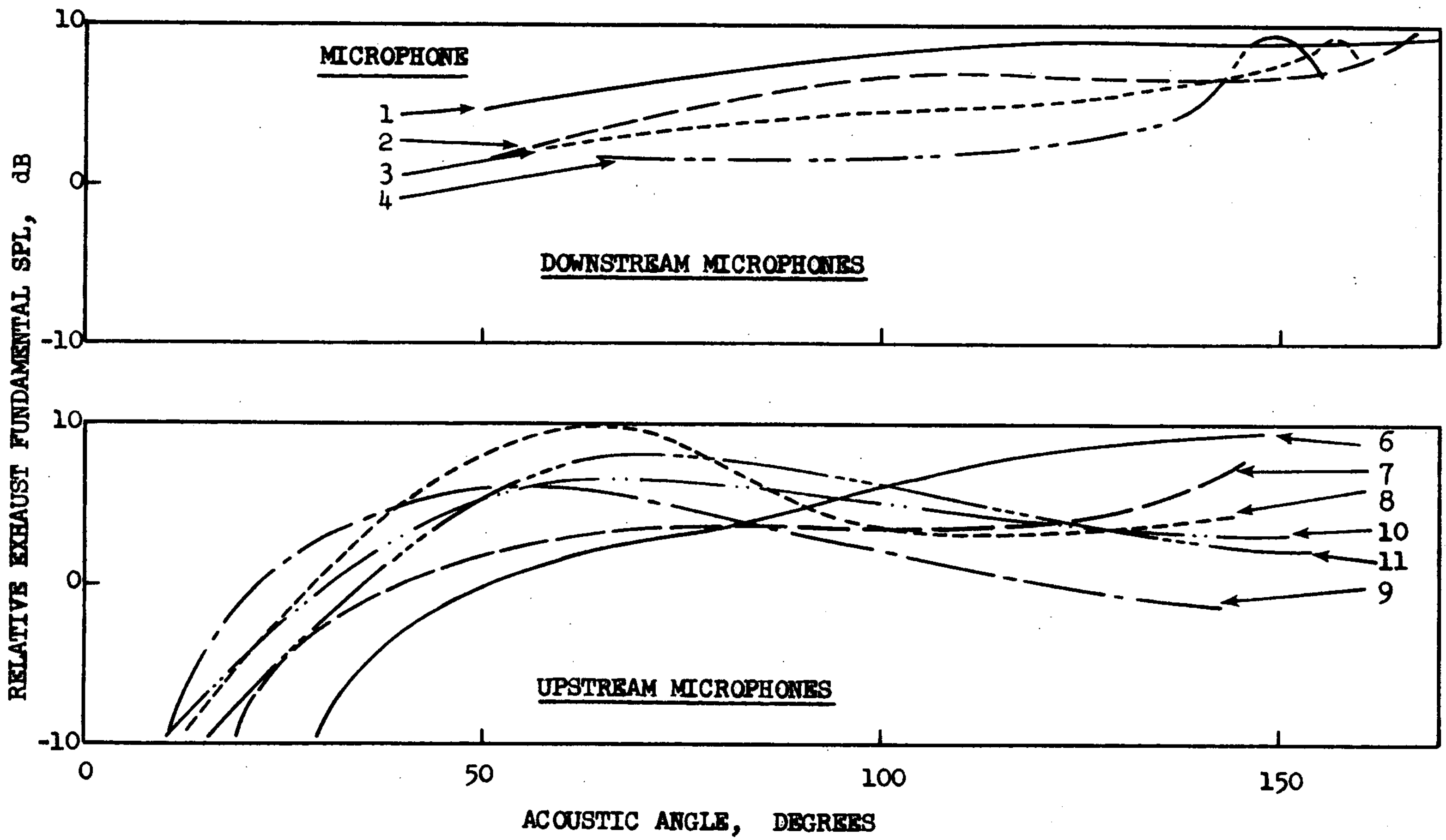


FIGURE 25 EXHAUST FUNDAMENTAL DIRECTIVITY PATTERN OF V/STOL MODEL LIFT/CRUISE FANS.

- FANS 3 & 4 @ 3600 RPM
- REFERENCED TO 120' RADIUS (36.6m)
- $\delta_{cn}=0°$ (EXTRAPOLATED DATA)
- SOLID SYMBOLS DENOTE DOWNSTREAM MICROPHONES

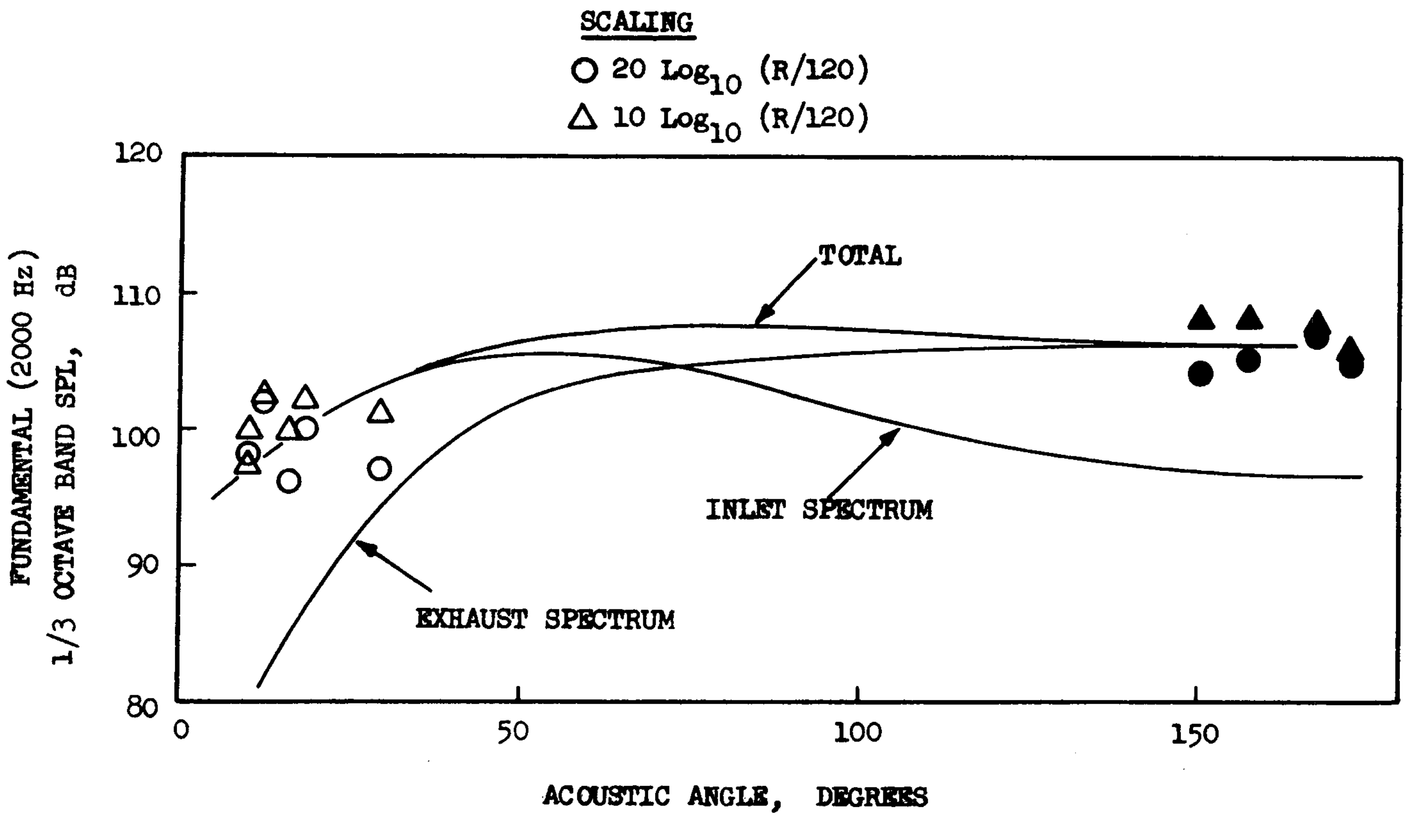


FIGURE 26 COMPARISON OF DISTANCE SCALING ON DIRECTIVITY PATTERN OF V/STOL MODEL LIFT/CRUISE FANS.

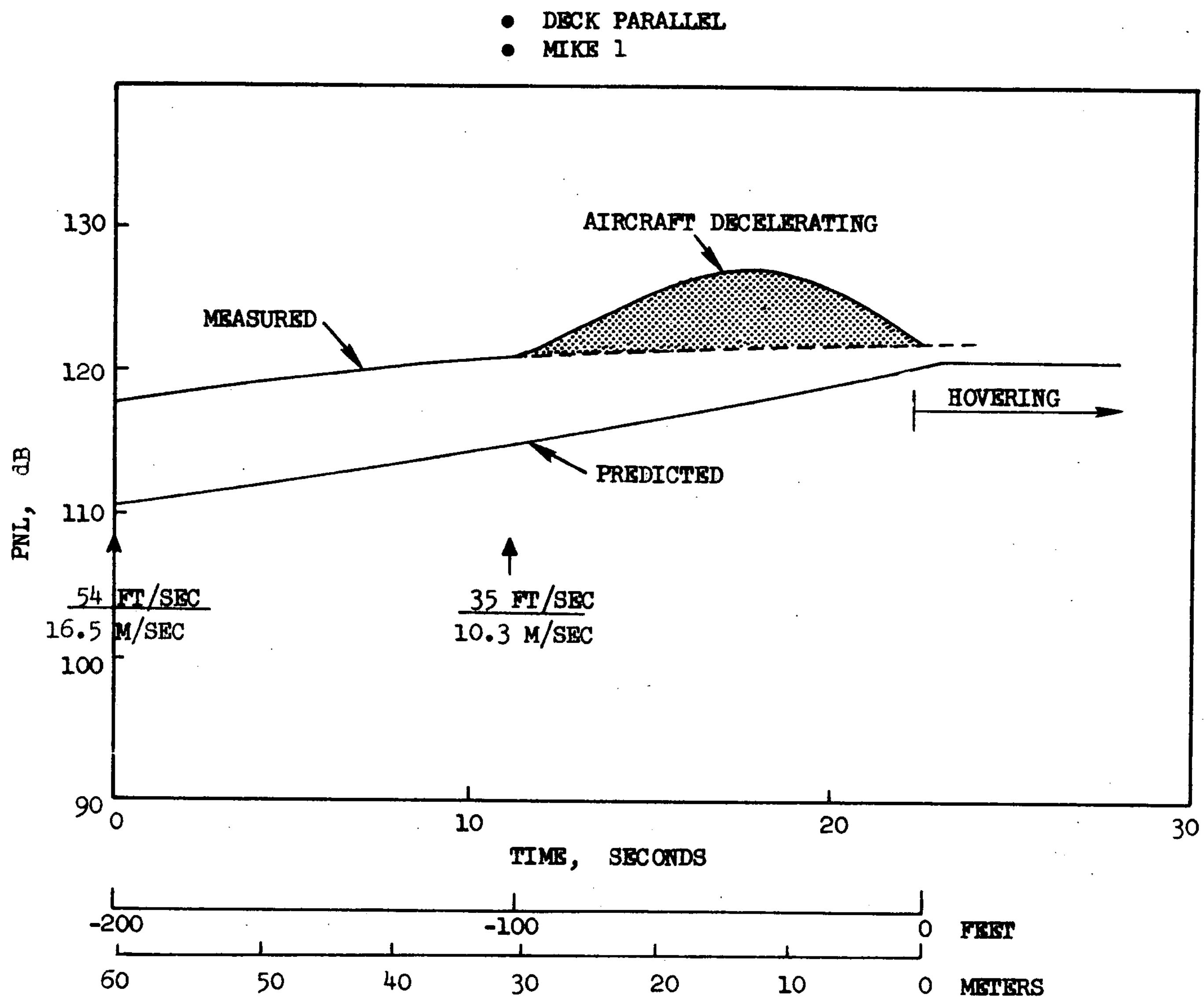


FIGURE 27 XV5B APPROACH NOISE MEASUREMENTS.

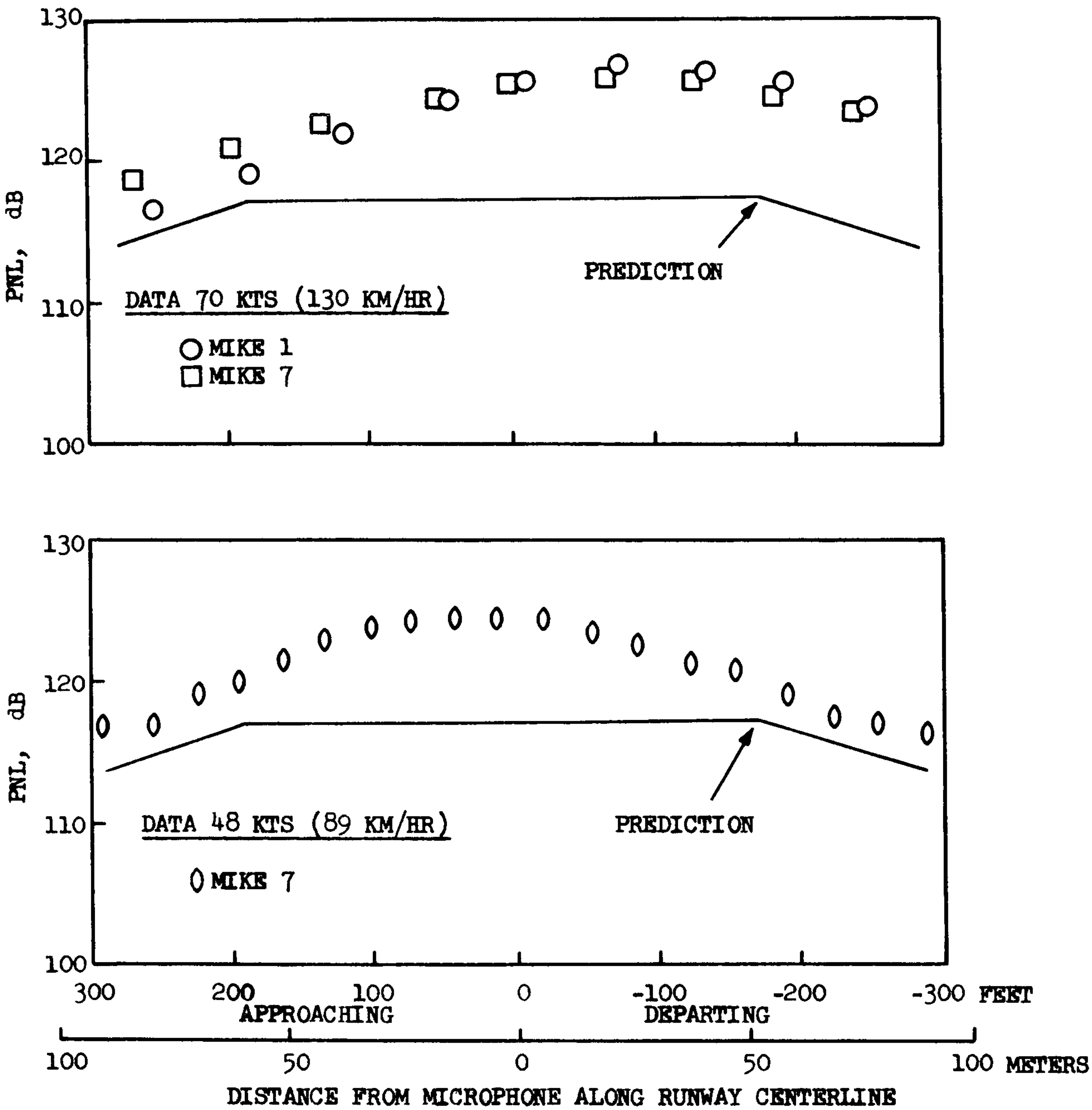


FIGURE 28 XV5B LEVEL FLYOVER NOISE MEASUREMENT, 150' (45.7m) ALTITUDE.

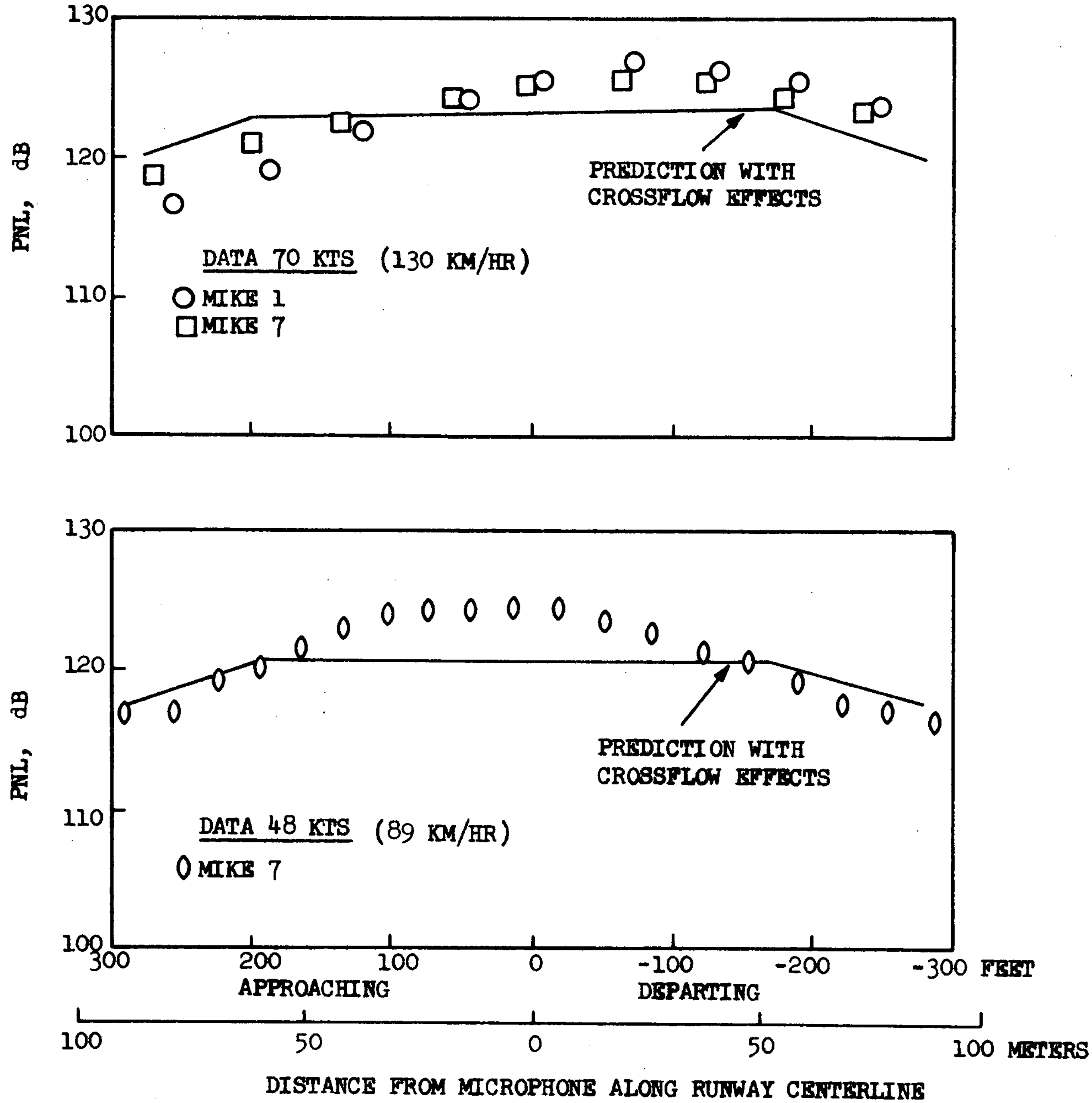


FIGURE 29 XV5B LEVEL FLYOVER NOISE MEASUREMENT, 150' (45.7m) ALTITUDE.

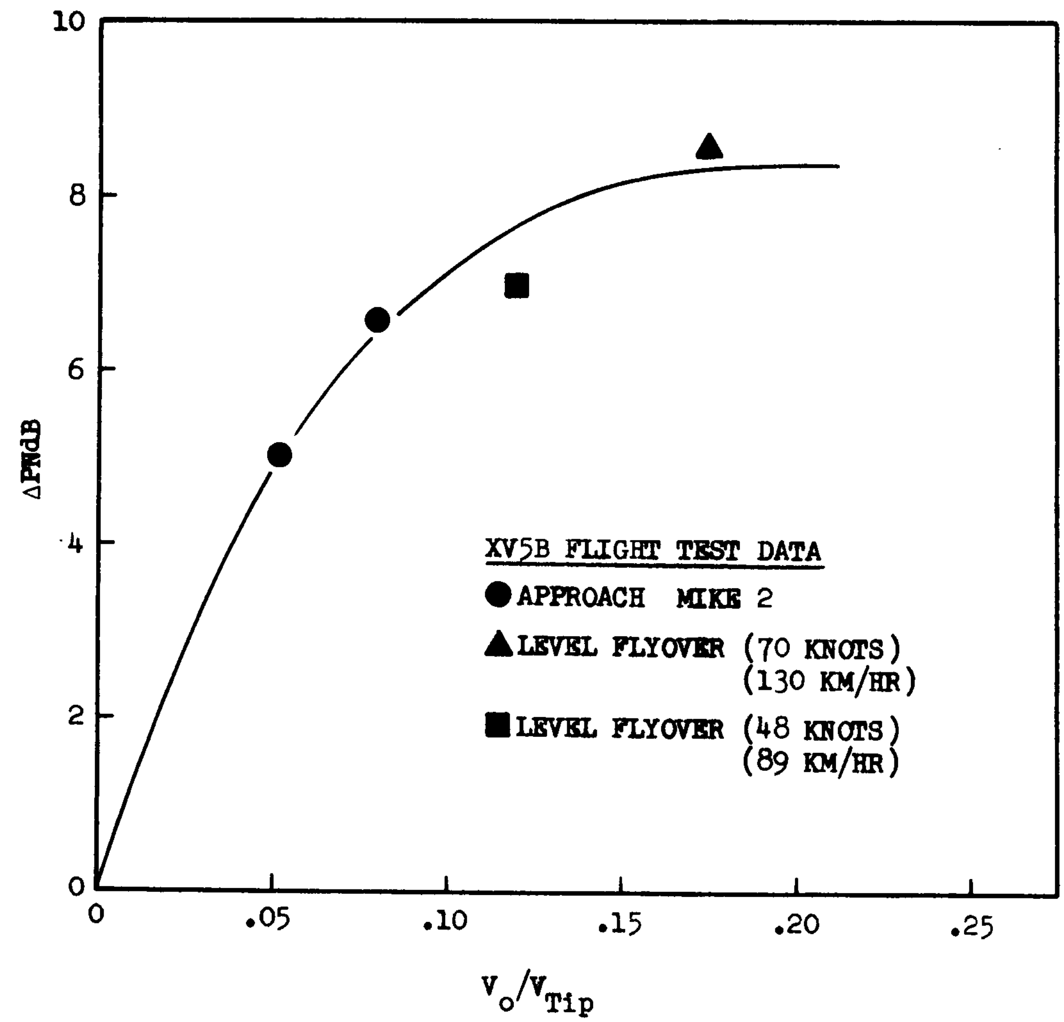


FIGURE 30 EFFECT OF CROSSFLOW ON LIFT FAN NOISE.

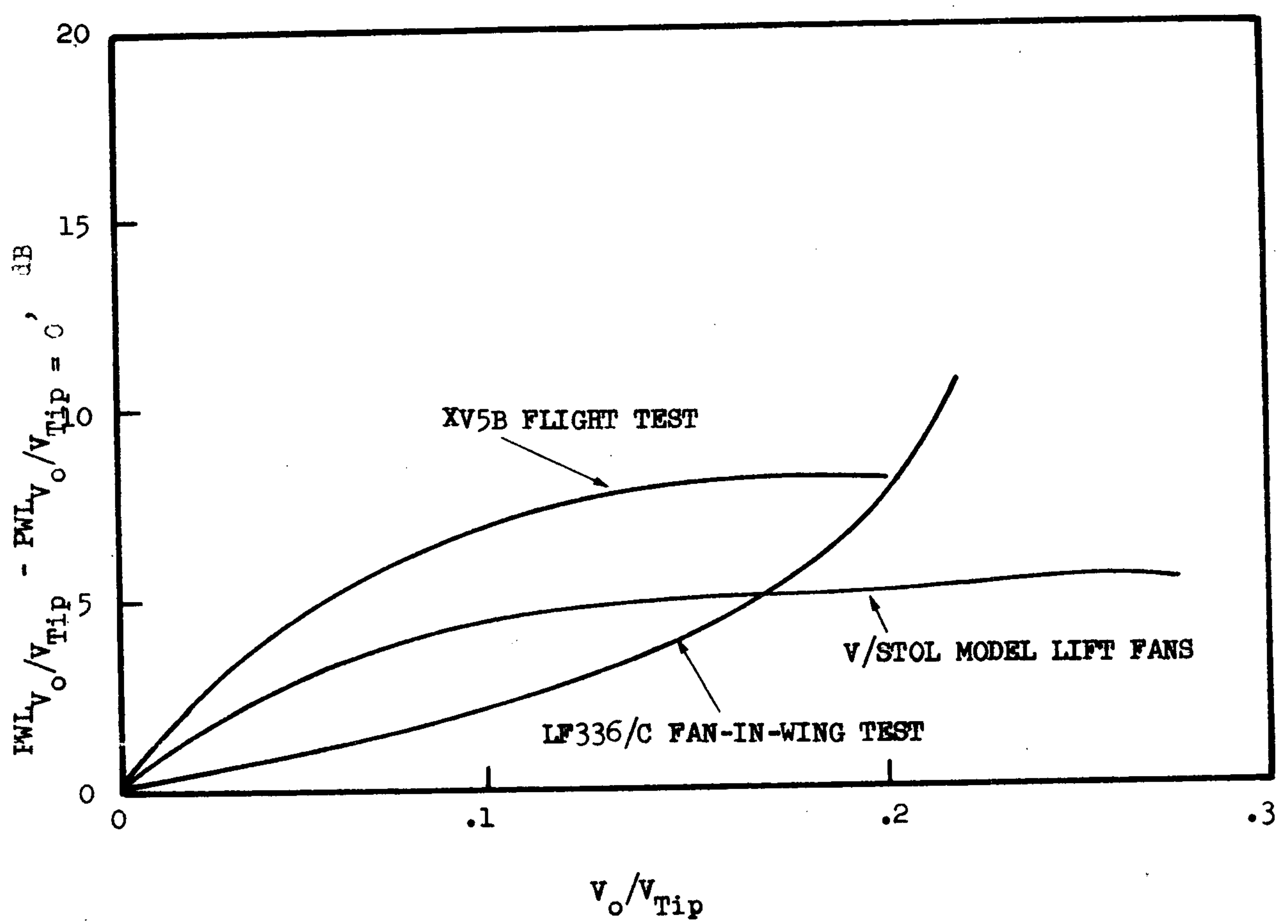


FIGURE 31 COMPARISON OF CROSSFLOW EFFECT ON NOISE LEVELS OF DIFFERENT LIFT FANS.

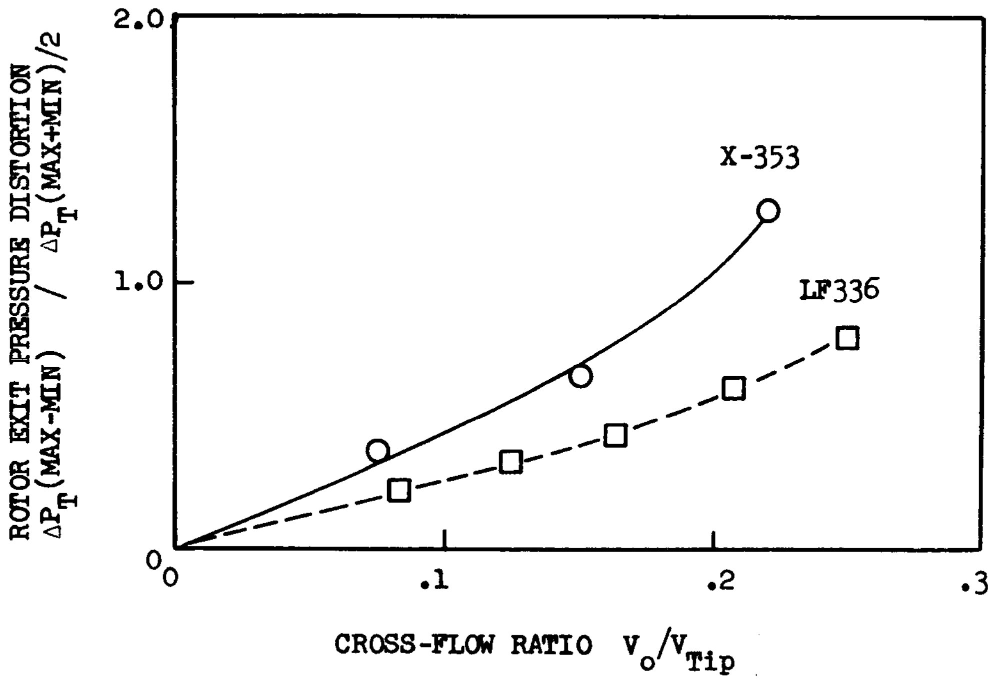


FIGURE 32 LIFT FAN ROTOR EXIT DISTORTION.

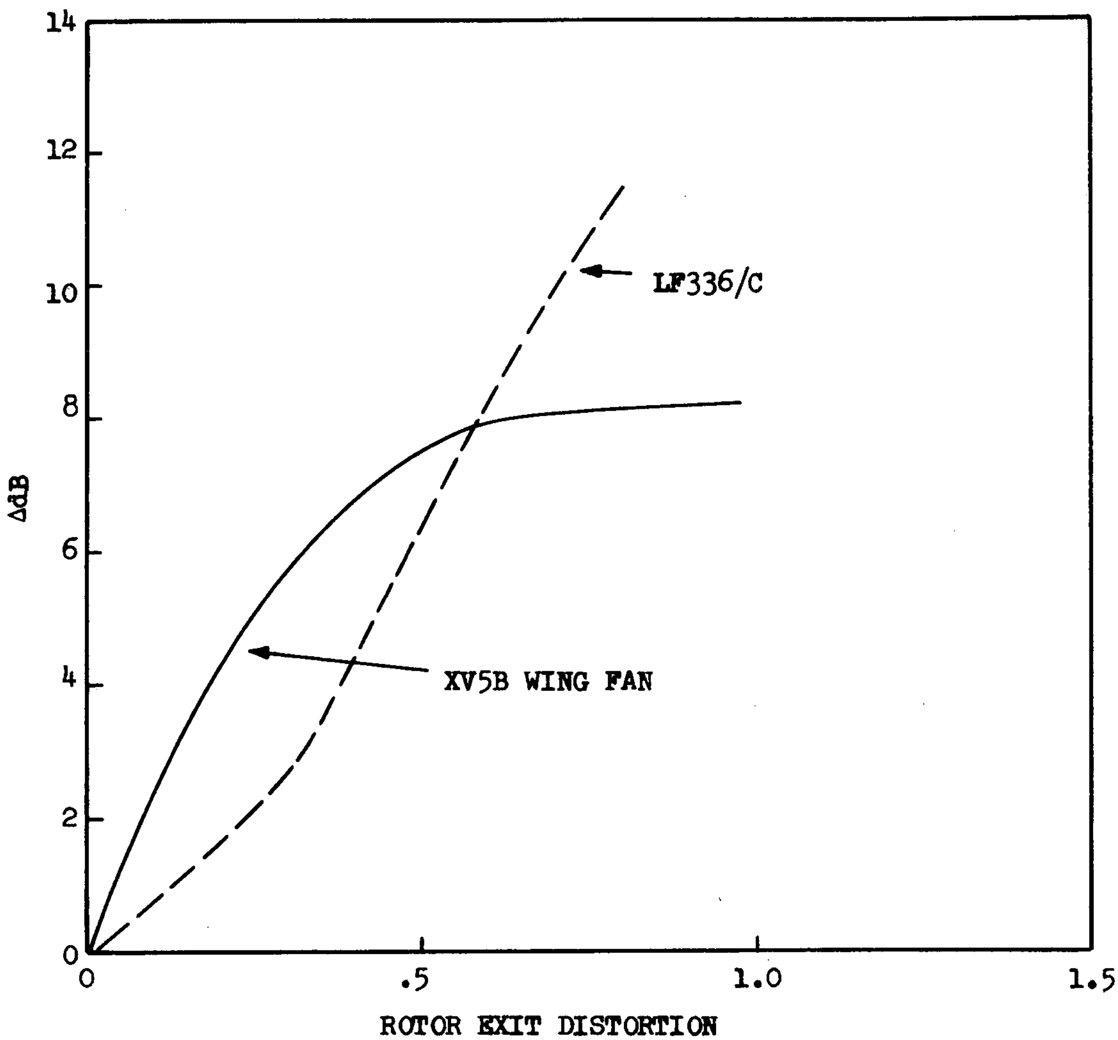


FIGURE 33 EFFECT OF DISTORTION DUE TO CROSSFLOW ON LIFT FAN NOISE.

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