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THE EFFECTS OF FORWARD SPEED ON FAN INLET TURBULENCE AND ITS RELATION TO TONE NOISE GENERATION

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SYMBOLS

A_{HL}	cross-sectional area based on nacelle leading edge diameter, cm^2 (in^2)
A_{TH}	fan nacelle throat area, cm^2 (in^2)
BPF	blade passing frequency, Hz
ℓ	turbulence length scale, m(ft)
L	fan cowl length, cm(in)
N	number of blades intercepting a turbulence eddy (see ref. 2)
r	nacelle radius, cm(in)
rpm	corrected fan rotational speed, rev/min
$R(\tau)$	autocorrelation coefficient
SPL	sound pressure level, dB
τ	time delay, sec or msec
u', v', w'	streamwise and transverse (radial and tangential, respectively) components of fluctating velocity, m/sec (ft/sec)
V	local velocity, m/sec (ft/sec)
x	longitudinal distance measured from fan nacelle leading edge, cm(in)
θ	farfield acoustic angle measured from fan inlet rotational axis

Subscripts

i	inner
in	fan inlet
max	maximum
o	outer
∞	freestream

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SUMMARY

The results of an experimental investigation into the effect of forward speed on fan inlet turbulence are presented. The purpose of this program was to determine the feasibility of using a wind tunnel to simulate various flight conditions where turbulence of atmospheric origin enters the engine inlet. Disturbances of this type seem to play a key role in the generation of fan-tone noise. The investigation was conducted in the Ames 7- by 10-foot Wind Tunnel with a small-scale low-pressure-ratio fan. Results indicate that a wind tunnel of this size does produce large turbulence scale appropriate for simulation of atmospheric scale. But the tunnel's low turbulence intensity seems to cause results contrary to existing theories on the effects of fan inlet velocity ratio on turbulence scale. Limited results with artificially increased turbulence intensity removed this contradiction. Acoustic measurements again showed the impact of inlet turbulence on fan-tone noise.

INTRODUCTION

To aid the development of low-noise V/STOL aircraft, Ames is continuing its study of noise sources in axial flow fans. Previous work (refs. 1, 2, and 3) has documented the need to better understand the role of fan inlet turbulence in generating discrete tones at the blade passing frequency and its harmonics. Reference 2 paid particular attention to the impact of inlet turbulence scale on the generation of discrete tones. However, all these efforts have stopped short of dealing with the whole problem by not including forward speed effects. Reference 4 draws attention to this omission with limited data that shows a reduction in in-duct fan-tone noise with the introduction of forward speed. Without more supportive measurements of the inflow properties, one can only speculate as to what changed with the addition of forward speed. But it is important to view these results as guidelines for future work with the following emphasis: Unsteady inlet aerodynamics (whether traced to atmospheric turbulence, ground vortex interaction, inlet duct boundary layer, or inlet diffuser performance) has a significant effect on fan-tone noise. Any investigation of these mechanisms may be incomplete without evaluation both statically and with forward speed.

The difficulties associated with making appropriate measurements in flight make it desirable to simulate the effects of forward speed in a ground-based facility. The present investigation was conducted to examine the feasibility of using a wind tunnel to simulate various flight conditions where turbulence of atmospheric origin enters the fan inlet. Forward speed effects on inlet turbulence properties important to the tone noise generation process were measured.

MODEL AND APPARATUS

The small-scale fan used in this investigation is shown in figure 1 installed in the Ames 7- by 10-Foot Wind Tunnel. The model was mounted in the center of the tunnel test section on a single 35° swept strut. The general test setup is shown in figure 2. Pertinent fan specifications are listed in table 1. The fan rotor was driven by a variable speed electric motor. Support for the fan rotor was provided by 8 noncambered support struts that were located 4.5 blade chords downstream of the rotor. No inlet or outlet guide vanes were used. The fan was mounted in a cruise nacelle whose ordinates are listed in table 2. Maximum nacelle length-to-diameter ratio was 1.8. The inlet contraction ratio (A_{HL}/A_{TH}) was 1.28. As indicated in table 2, approximately a 10-cm section of constant inner and outer radius was inserted ahead of the fan rotor to provide spacing between the hotwire measurement plane and the rotor. This spacing was needed to minimize the rotor pressure field contamination of hot-wire signals. The cruise nacelle was designed without a diffusion section downstream of the throat to eliminate the effects of diffuser performance from this investigation.

TESTING PROCEDURE AND INSTRUMENTATION

Measurements of fan inlet turbulence were made with a hot-wire "x" probe which allows determination of two orthogonal turbulence components by summing and differencing voltages. Turbulence measurements inside the fan inlet were made in a plane at $x/L = 0.458$. Turbulence measurements outside the fan inlet were confined to an area midway between the tunnel side wall and the fan rotational axis and approximately one fan diameter upstream of the fan inlet and one-half fan diameter below the fan horizontal centerline.

Acoustic data were measured with a 1.27 cm(0.5 in.) diameter condenser microphone mounted on the sidewall of the tunnel in a horizontal plane through the fan axis of rotation. The microphone was located on a 3.048 m(10 foot) diagonal from the fan inlet (see fig. 2) giving a farfield angle of 30° from the fan rotational axis.

Hot-wire and microphone signals were FM-recorded on magnetic tape at 30 ips with a frequency response range of 0 to 10 kHz. All data analyses were performed from tape recorded data. Autocorrelation of turbulence data was made directly by the use of a correlation and probability analyzer. Turbulence and acoustic spectra were obtained from a realtime narrowband spectrum analyzer with integrating capability. All spectra presented were processed with a constant 25-Hz bandwidth.

Steady-state pressures measured included fan inlet static pressures at $x/L = 0.458$ and fan discharge total pressures at the nozzle exit plane.

The test program was run in the closed circuit 7- by 10-foot Wind Tunnel. The wind tunnel does not have screens or honeycomb sections installed in the settling chamber upstream of the test section.

RESULTS AND DISCUSSION

In viewing the results of this investigation, which attempted to provide some simulation of an actual flight condition, let us first recall the situation we tried to simulate. In actual aircraft engine operation, one source of fan inlet turbulence, postulated notably from reference 3 and from other tests at Ames, can be caused by atmospheric turbulence. An appropriate investigation would be examination of fan inlet turbulence scale and intensity as the engine is operated from a static condition to forward speed. But, unlike outdoor testing where atmospheric turbulence is available for both static and forward speed conditions, wind tunnel simulation does not naturally provide turbulence with the same origin for both static and forward speed operation. The wind tunnel requires venting to permit static fan operation without inducing tunnel flow; thus, the resultant turbulence properties become a function of the vented environment. These turbulence properties are not the same as those of the wind-tunnel flow used for forward speed. Consequently, although this investigation examines forward speed effects, it does not include the transition region from static operation to forward speed. It seems imperative, however, that this transition region must not be omitted from future investigations.

Turbulence Measurements

Initial measurements were made to establish the turbulence intensity and streamwise length scale of the wind-tunnel flow. Autocorrelations of u' and w' components were used to determine turbulence length scale and intensity. Since both turbulence components showed similar trends, only the transverse w' component is presented. Figure 3 shows autocorrelations of w' for several tunnel velocities. The lowest tunnel velocity of 5.45 m/sec was obtained without the tunnel operating but with the model fan running and pumping the tunnel. The computed tunnel turbulence scale is large for all forward speeds and indicative of atmospheric scales. As would be expected, the turbulence intensities are low.

Autocorrelation measurements were then made to determine the resulting turbulence structure of the flow inside the fan inlet. These measurements are shown in figures 4 and 5 for several fan inlet velocity ratios. Velocity ratio was varied in figure 4 by maintaining a nominal fan rpm and varying the tunnel velocity, whereas in figure 5, tunnel velocity was held constant and fan rpm varied. The results show little change in turbulence intensity and a dramatic reduction in scale when compared to the tunnel flow values of figure 3. Figure 6 shows representative turbulence spectra that correspond to the autocorrelated data in figure 3(b) and figure 4(b), respectively. These spectra support the correlation function characteristics. Figure 7 summarizes the effects of forward speed on fan inlet turbulence scale. In this figure, fan inlet turbulence scale is normalized by the corresponding tunnel turbulence scale and plotted versus fan inlet velocity ratio. The data show that the fan inlet turbulence scale was considerably smaller than the tunnel scale and increased with increasing velocity ratio. These results are contrary to expectations. From Prandtl's formulation, a flow contraction (taken here as the fan inlet) should increase the turbulence scale in the streamwise direction in proportion to the ratio of the downstream velocity to the upstream velocity. Since the inlet turbulence scale controls the generation of tone noise, the effects on scale were pursued. It was assumed that the low tunnel turbulence intensity could have affected the results. To increase tunnel turbulence intensity, a rectangular obstruction 1.97-m high and 0.492-m long (streamwise) was placed 10 streamwise dimensions of the object upstream of the model fan. With the model fan operating and pumping the tunnel, measurements were made at the lowest inlet velocity ratio. Figure 8 presents these results. Notice that, with the obstacle installed, the turbulence scale inside the fan inlet is larger than outside and more closely fits the Prandtl model. The measured turbulence intensity was about 1.3% and not excessive in view of average levels encountered in actual flight. Additional measurements were attempted at various tunnel speeds, but were unsuccessful due to the lack of a satisfactory method to input turbulence of controlled intensity and scale.

As documented in reference 2, sufficient turbulence scale ($N \geqslant 1$) gives rise to tone noise generation, and is verified by the results shown by figure 9. Here, acoustic spectra are compared with the fan operating in the basic tunnel flow condition and with the artificially induced condition shown in figure 8. The increase in fan-tone noise at the blade passing harmonics is quite evident. Measurement of the acoustic spectra was made by placing a microphone on the tunnel sidewall so as not to perturb fan inflow. Notice also, by comparing figures 4(a) and 8(b), that the tone noise increase was accompanied by increased turbulence scale and intensity. An additional comment should be made here concerning the role of turbulence scale. Because of the initial contrary results obtained for streamwise scale in this investigation, efforts were concentrated on this aspect; lateral scale was not measured. It must be remembered that lateral scale also affects the generation of tones. In outdoor tests (ref. 3), measurements have shown that lateral turbulence scale occupies only a small portion of the fan circumference. Consequently, this type of a disturbance can provide the impulsive blade loading requirement (ref. 5) that is necessary to generate noise well into the blade passing harmonics.

In the final analysis, the present program has not provided conclusive answers to posed questions but it is hoped that guidelines have been laid for future work.

CONCLUDING REMARKS

A wind tunnel has been used to simulate the effects of forward speed on fan inlet turbulence properties. Although the investigation was limited in scope, several conclusions can be made. It appears that a typical low-turbulence wind tunnel, so commonly used for conventional fan inlet performance studies, may not be adequate for the investigation of inlet turbulence-related noise sources. While a wind tunnel can produce large streamwise turbulence scales that are appropriate for simulation of atmospheric scales, its low turbulence levels seem to cause results contrary to existing theories on the variation of turbulence scale with fan inlet velocity ratio. Limited results with artificially increased turbulence intensity removed this contradiction. Work with artificially induced turbulence embedded in the wind-tunnel flow must be continued and must encompass a range of forward speeds. Turbulence intensity must be more representative of that encountered in actual flight and of sufficient scale.

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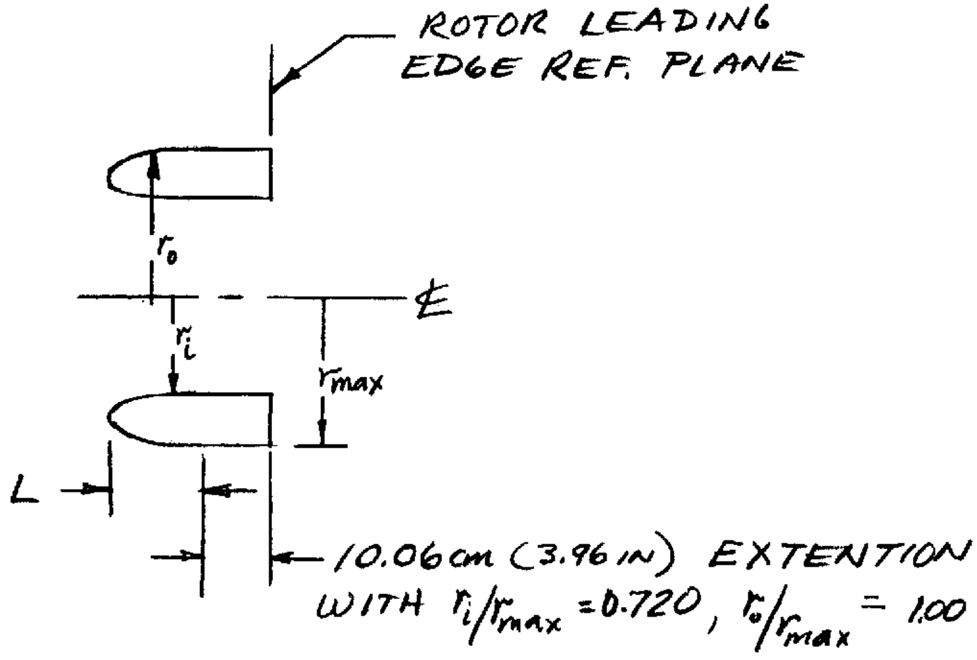
FAN ROTOR DIA.	0.3m (0.99 ft)
HUB-TIP RATIO	0.48
TIP SOLIDITY	0.71
BLADE NUMBER	15
FAN PRESSURE RATIO	1.015
MAX. RPM	7600
FAN TIP SPEED	119.8 m/sec (393 ft/sec)

TABLE 1. MODEL FAN SPECIFICATIONS.

NACA INLET DESIGNATION – 1-81-33 (MODIFIED)

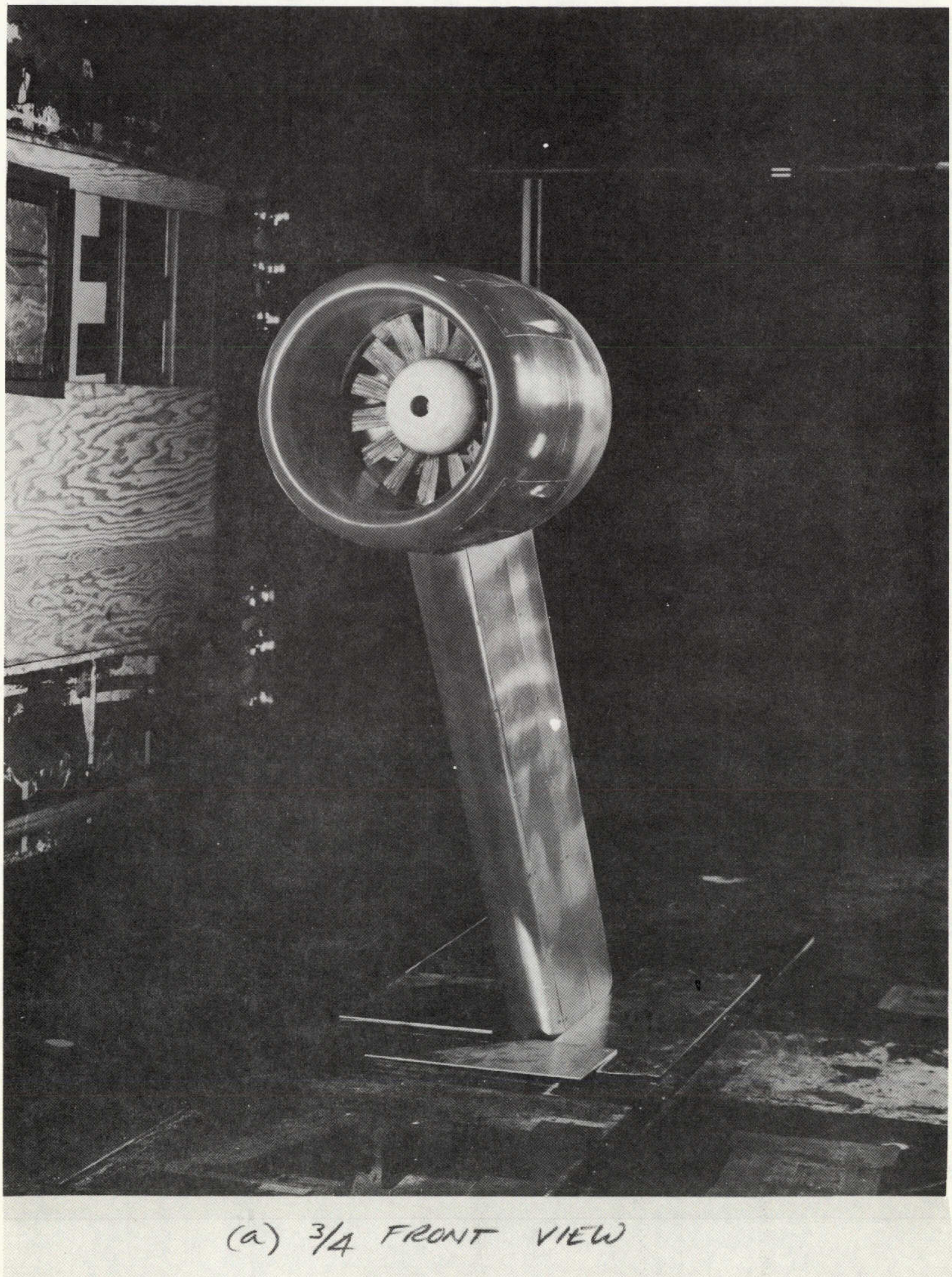
x/L	r_i/r_{max}	r_o/r_{max}
0.000	0.816	0.816
.010		.838
.015	.787	
.020		.848
.030	.779	.856
.060	.765	.879
.090	.755	.890
.150	.741	.914
.300	.723	.954
.392	.720	.986
.500	.720	
.727	.720	.999
.750	.720	1.000
1.000	.720	1.000

L, cm	L, IN.	r_{max}, cm	r_{max}, IN
13.97	5.50	21.16	8.33



10.06 cm (3.96 IN) EXTENTION WITH $r_i/r_{max} = 0.720$, $r_o/r_{max} = 1.00$

TABLE 2. – LIST OF FAN INLET AND COWL ORDINATES.



(a) 3/4 FRONT VIEW

FIGURE 1.- PHOTOGRAPH OF MODEL FAN MOUNTED IN AMES 7x10-FOOT WIND TUNNEL

(b) 3/4 REAR VIEW

FIGURE 1. - CONCLUDED.

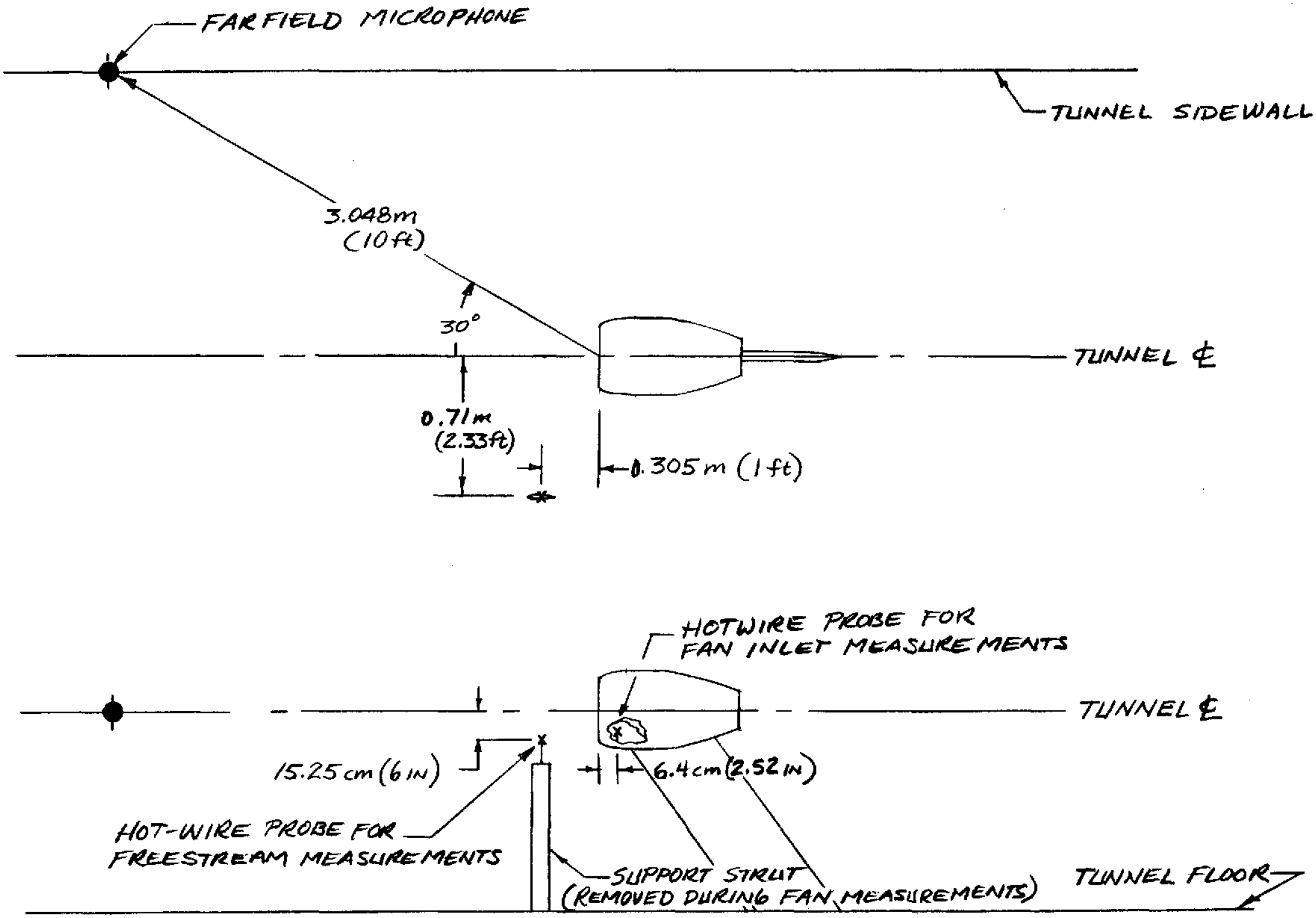


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FIG 2.- SCHEMATIC OF TEST SETUP IN 7x10-FOOT WIND TUNNEL.

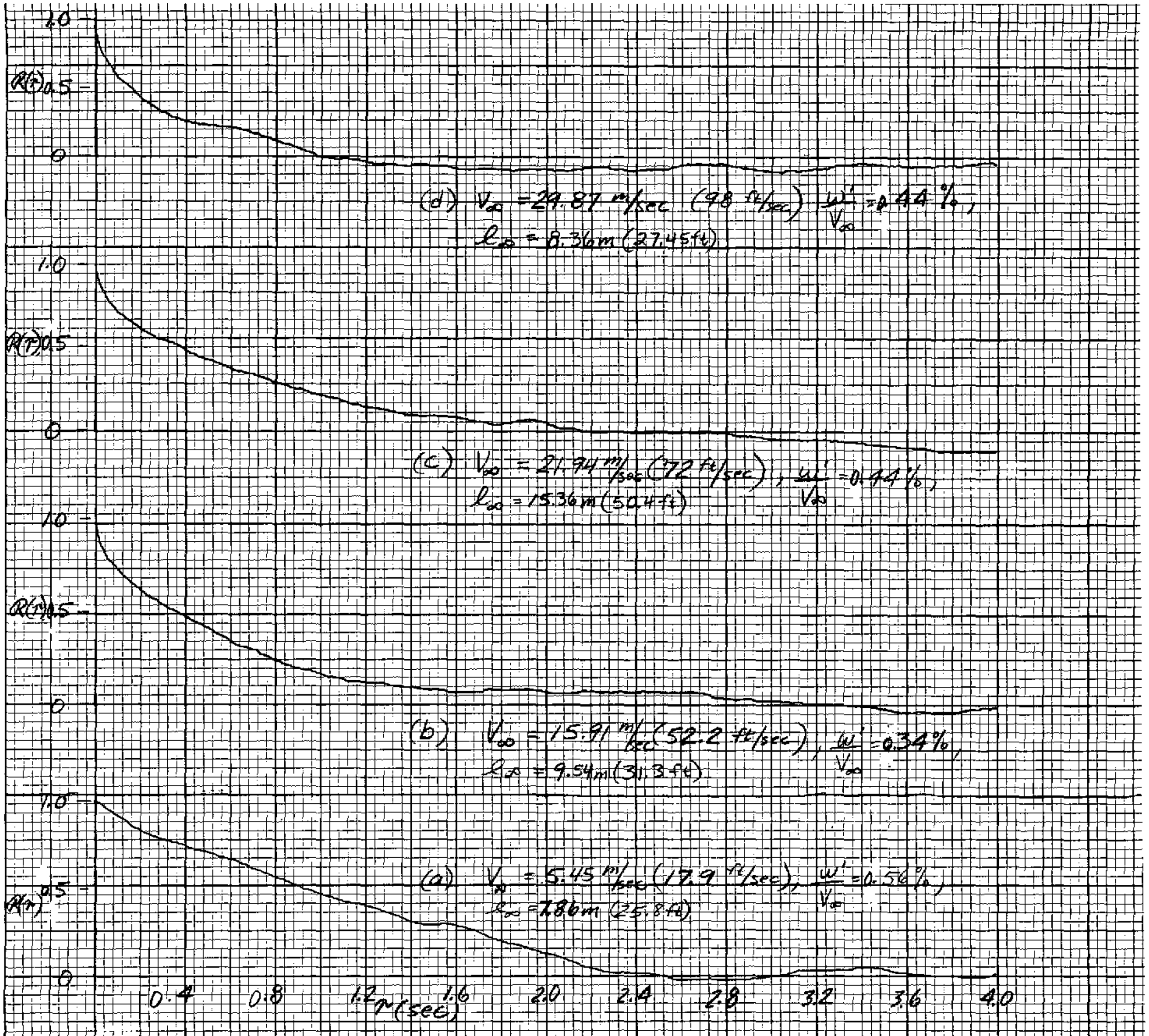


FIG 3. — AUTOCORRELATION OF BASIC TUNNEL FREESTREAM TURBULENCE; W' TURBULENCE COMPONENT.

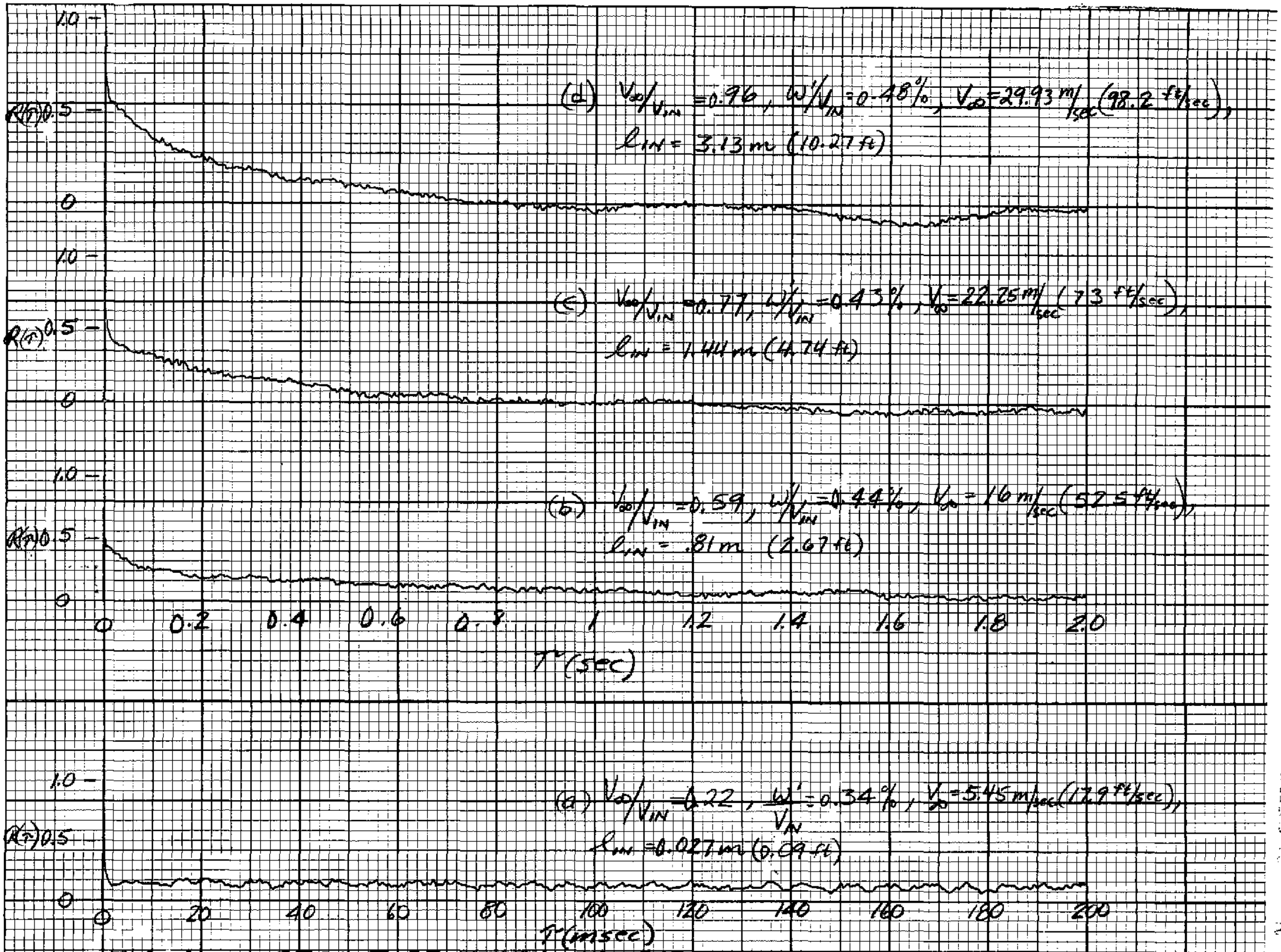


FIG 4 EFFECT OF VELOCITY RATIO ON FAN INLET TURBULENCE LENGTH SCALE. FAN RPM = 99%.

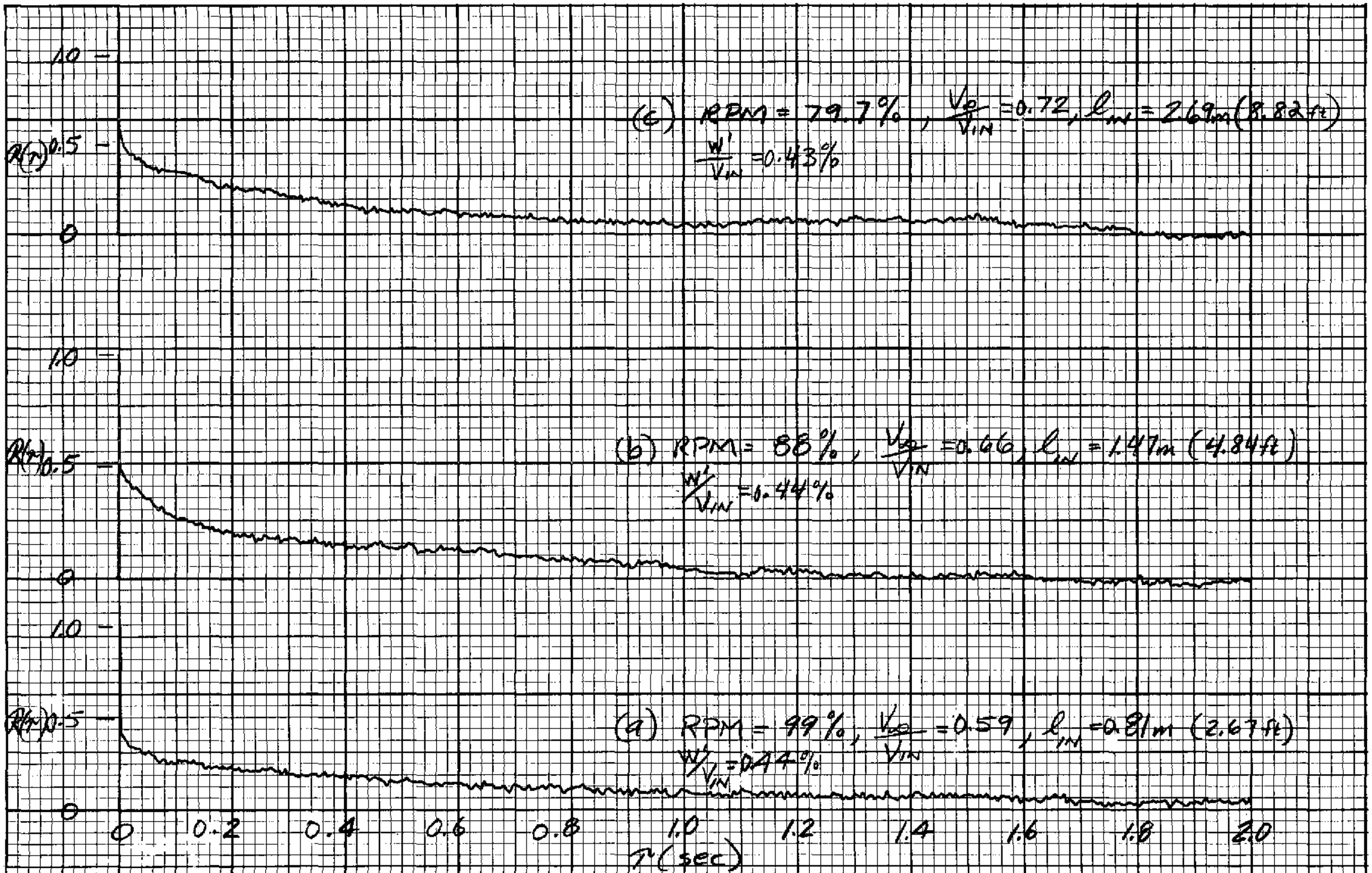
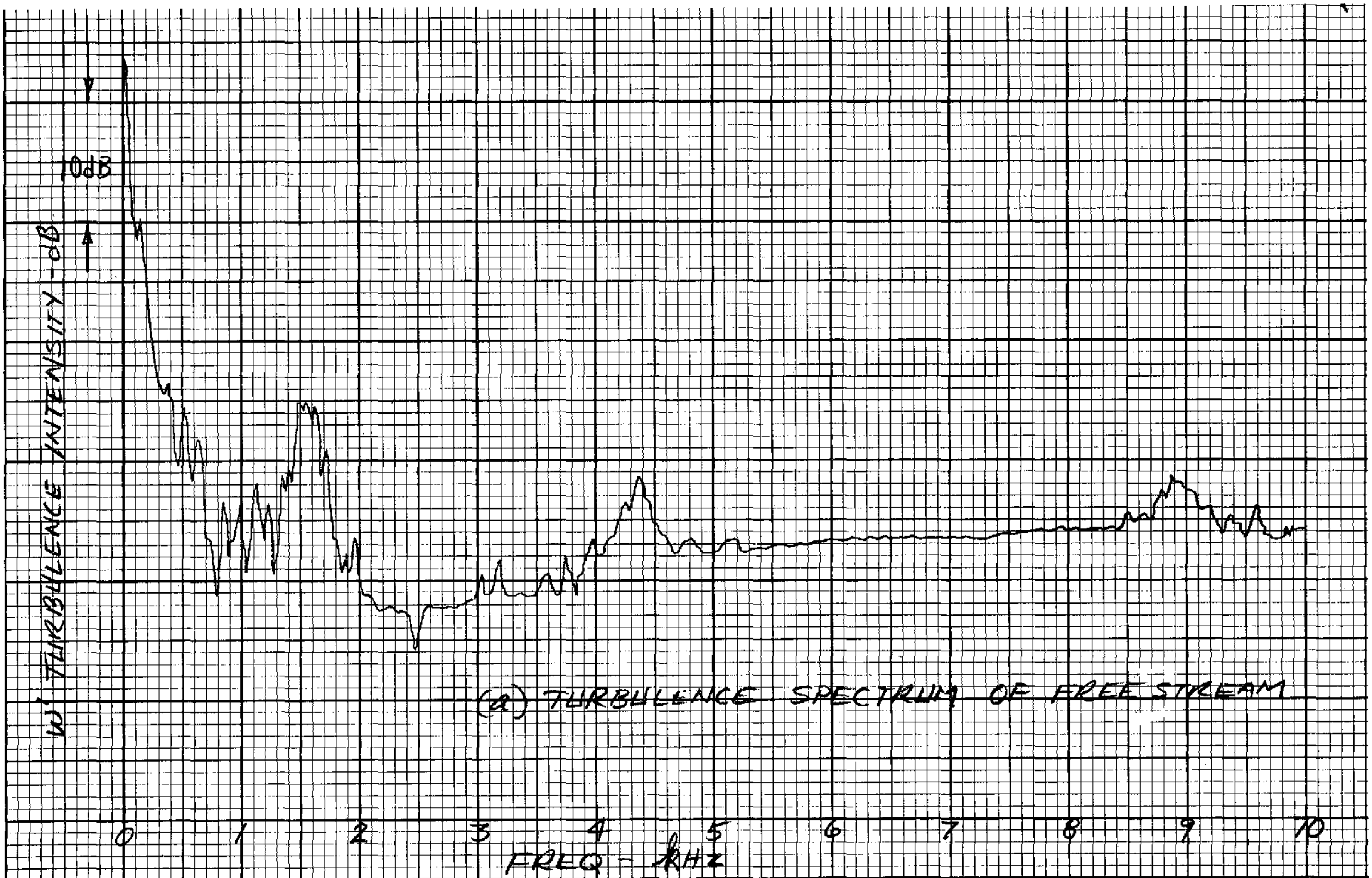
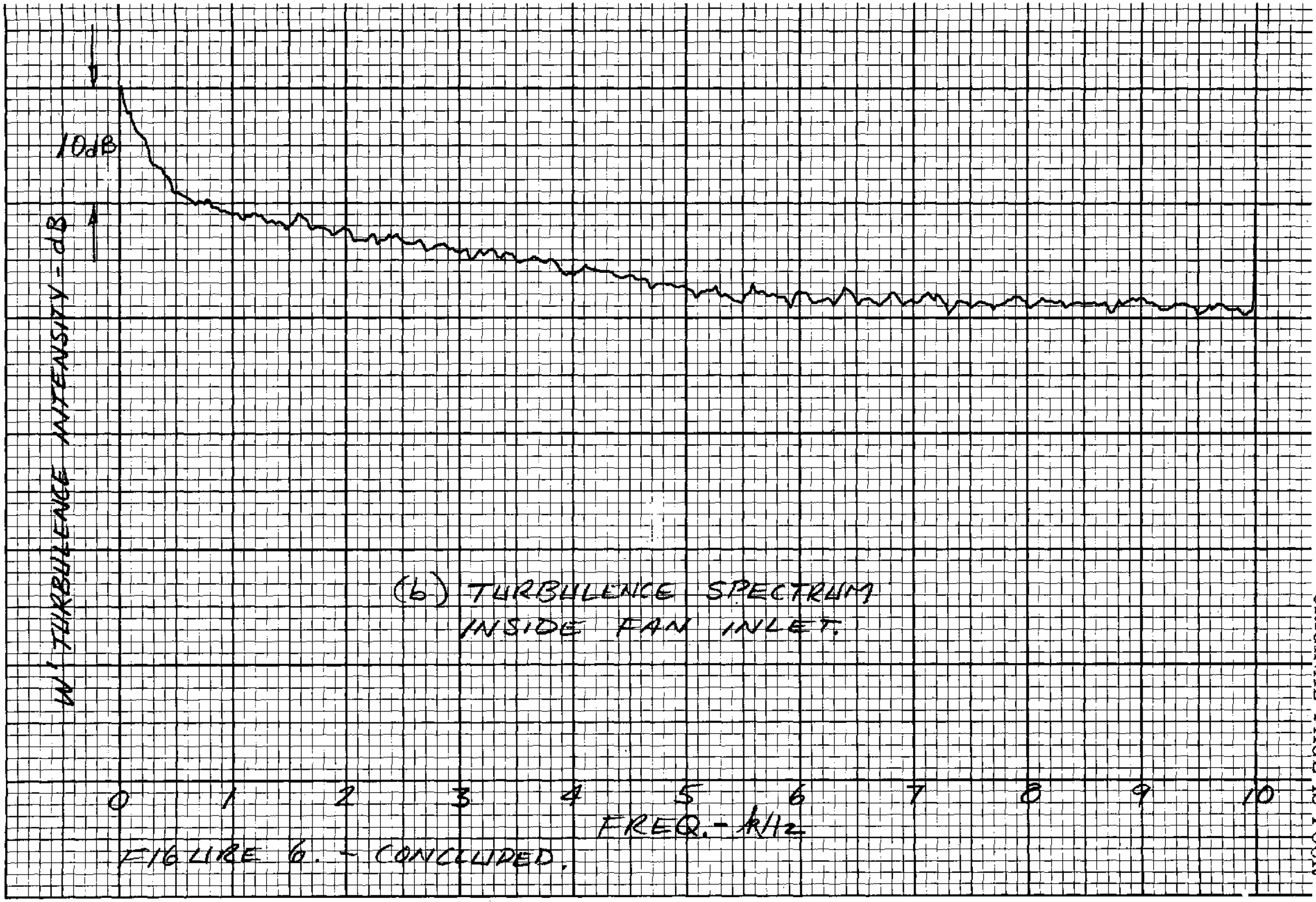


FIG 5 - EFFECT OF VELOCITY RATIO ON FAN INLET TURBULENCE LENGTH SCALE. V_∞ = 15.84 m/sec (52 ft/sec)



(a) TURBULENCE SPECTRUM OF FREE STREAM

Fig. 6. – TYPICAL TURBULENCE SPECTRA FOR W' COMPONENT.



(b) TURBULENCE SPECTRUM INSIDE FAN INLET.

FIGURE 6. - CONCLUDED.

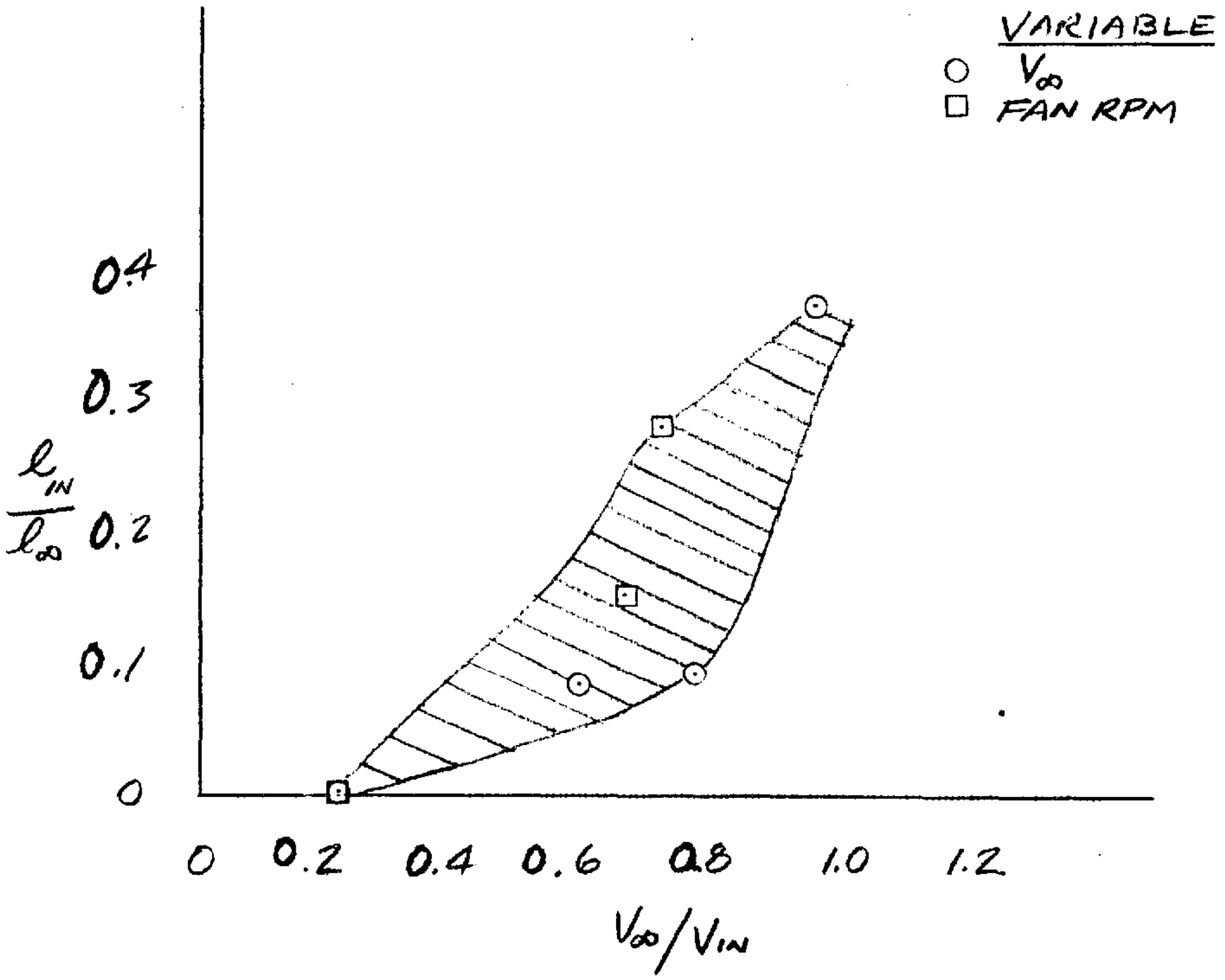


FIG 7.— SUMMARY OF FAN INLET VELOCITY RATIO EFFECTS ON INLET TURBULENCE LENGTH SCALE.

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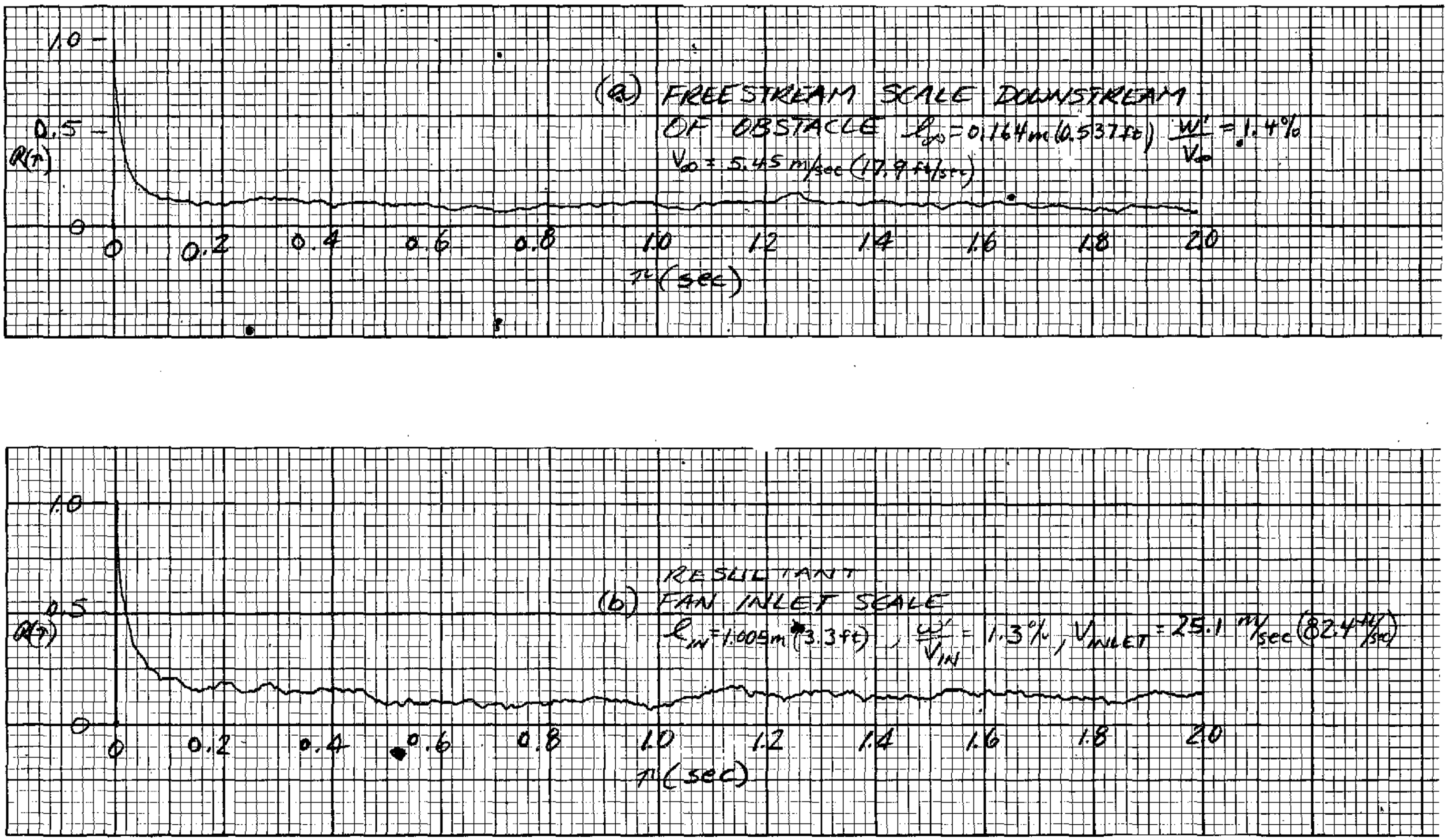
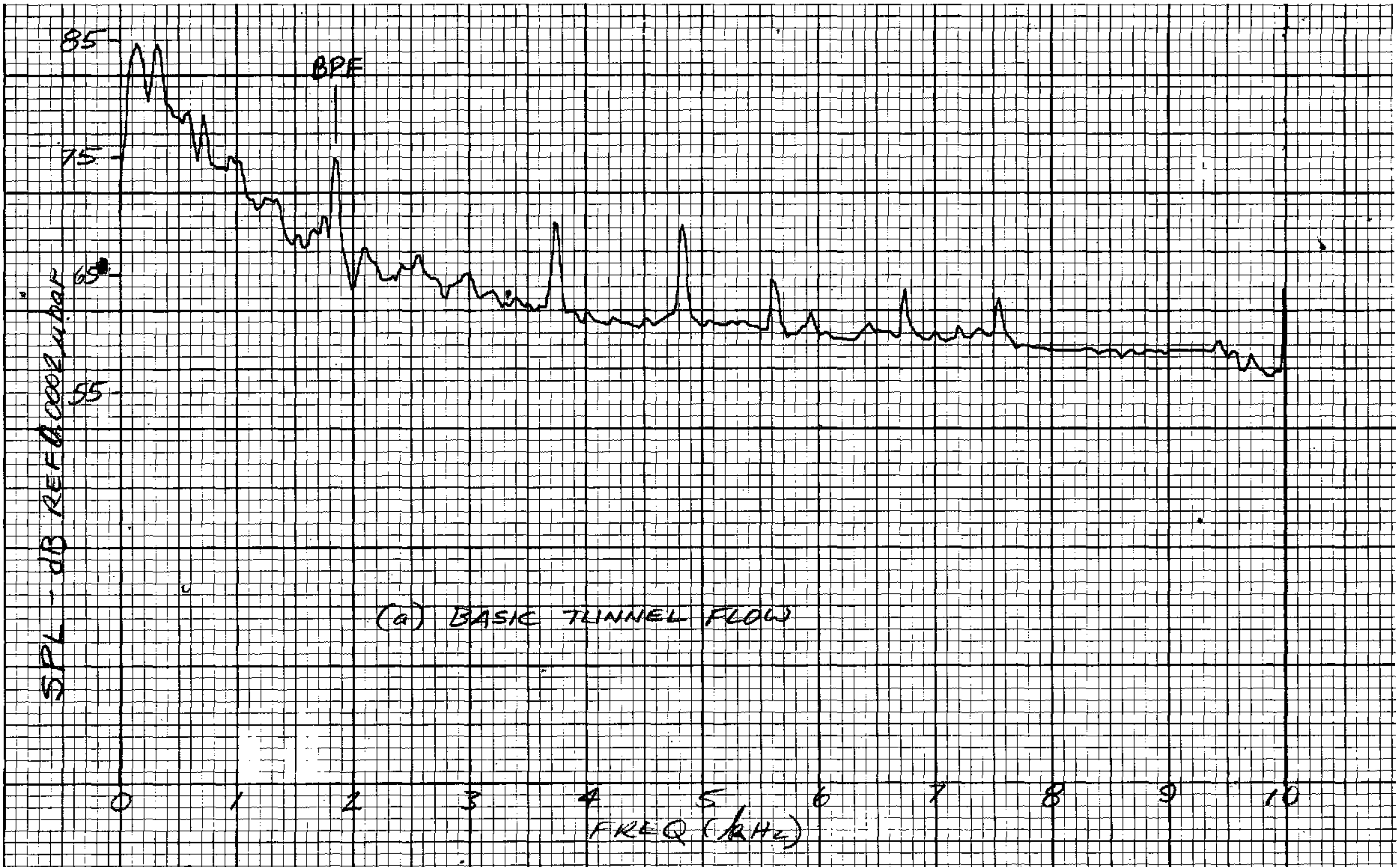


FIG 8 .— EFFECT OF FAN INLET VELOCITY RATIO ON TURBULENCE SCALE WITH INCREASED TURBULENCE INTENSITY. FAN RPM = 99%, V_∞/V_{IN} = 0.217.



(a) BASIC TUNNEL FLOW

FIG 9. — EFFECT OF INCREASED INLET TURBULENCE LENGTH SCALE AND INTENSITY ON FAN-TONE NOISE. $\theta = 30°$, $V_\infty / V_{IN} = 0.217$ $V_\infty = 5.45$ m/sec (17.9 ft/sec).

FIGURE 9. - CONCLUDED.