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NOISE DUE TO INTERACTION OF INLET TURBULENCE AND GUIDE VANE SECONDARY FLOW WITH PROPULSOR

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The objective of this investigation is to study the radiated sound from a propulsor rotating blade row due to operation in various types of turbulent inflows; control surface wakes, hub and annulus wall boundary layers, and secondary flow. Each type of inflow exists in a typical underwater vehicle with struts or control surfaces upstream of the propulsor.

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INTRODUCTION

The directly radiated noise from propulsors can be related to the time-dependent pressures on the blades due to operating in a fluctuating velocity field. The velocity field at the propulsor inlet of a typical vehicle contains both spatially and temporally varying velocity components. The spatial variations in steady velocity are due to wakes from control surfaces, struts, and protuberances from the hull and due to the hull boundary layer. The temporal variations are due to turbulence in the propulsor inflow field and time-dependent motions of the vehicle. The turbulent velocity fluctuations occur in the hull boundary layer, in the wakes shed from control surfaces, and in the secondary flow field which is generated at the intersection of each control surface and the hull.

Extensive studies of the spatial variations in steady velocity, the resulting blade passing frequency time-dependent shaft thrust, and the resulting radiated noise have been made.

The mechanism by which the incident turbulence (both in the wake and in the boundary layer) generate noise are two-fold: (a) quadrupole sources: The turbulence provides a mechanism by which the potential flow field around the rotor is scattered as sound. Ffowcs-Williams and Hawkings [1] first pointed out this effect. (b) Dipole sources: The non-uniform velocity field associated with turbulence produces fluctuations in angle of attack to the blade row leading to the unsteady forces and noise generation. This gives rise to dipole sources on the blade surfaces.

Previous theoretical investigations of dipole sound radiation due to the operation of a rotor in a turbulent inflow have been carried out by Sevik [2], Mani [3], and Lowson [4]. In Sevik and Mani's analyses, the turbulent inflow is assumed to be homogeneous and isotropic. The lift fluctuations over the span of a typical blade are determined. The aerodynamic response function is chosen to be that developed by Sears [5]. This function is based on two-dimensional incompressible, thin-airfoil aerodynamics and ignores mutual interference between blade elements. Hanson [6] predicted the noise due to atmospheric turbulence using random pulse modulation theory.

Preliminary investigations, both experimental and theoretical, have been made on the turbulence induced noise. Robbins and Lakshminarayana [7] studied, experimentally, the sound generated by the interaction of inlet turbulence (nearly isotropic) with a propulsor, using air as the test medium. The results indicate a definite increase in overall sound pressure level and an increase in the spectrum level with the increase in turbulence intensity. For integral scales smaller than the blade spacing, the total sound power is found to be proportional to the square of the ratio (turbulence velocity/integral length), where turbulence velocity is the rms value normal to the blade chord.

The objective of the present investigation is to study the radiated sound from the rotating blade row of a propulsor due to operation in turbulent inflows. Turbulent flows of interest for typical underwater vehicles are currently being investigated, i.e., wall boundary layers and wakes from struts and control surfaces. It is planned to continue this investigation as well as extend it to include secondary flows due to guide vane [8] interacting with a rotor. The latter effect, which has been suspected to be a source of pure tone noise as well as broadband noise, has never been studied before.

OBJECTIVES OF THE INVESTIGATION

The objective of the investigation is to study, experimentally and analytically, the sound generation due to the following sources:

1. Turbulence in upstream boundary layers
2. Turbulence in guide vane or control surface wakes
3. Secondary flow upstream of the rotor blade row

The relationship between the turbulence properties (length-scale, spectrum, intensity, etc.), rotor and flow parameters, and radiated sound are not properly understood. Furthermore, very little is known on the noise generated due to secondary flow upstream of the rotor blade row. It is the intent of this investigation to gain some basic information concerning the interaction of these factors in producing the acoustic field and to develop generalized theories for predicting these effects.

TURBOMACHINERY NOISE FACILITY AND METHOD OF GENERATING VARIOUS ENTRY FLOWS

The experimental investigation is being carried out using a test rotor with variable number of blades. The flow medium is air. The experimental facility that exists for this study consists of four main components: a large acoustically treated enclosure surrounding the fan inlet, the test rotor, a sound absorbing chamber downstream of the fan, and an auxiliary Joy axial flow fan. A drawing of the assembly is shown in Figure 1.

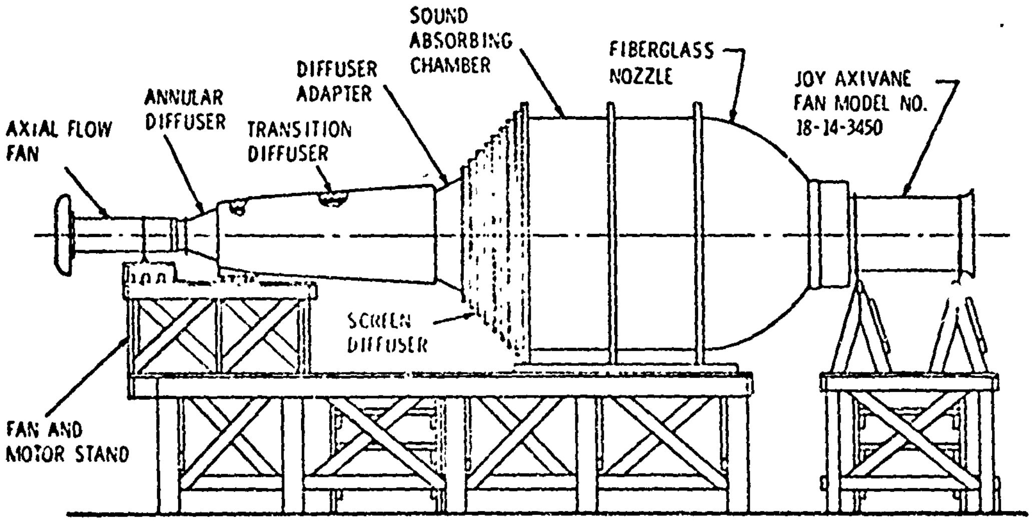

Figure 1: Aeroacoustic Facility

The inside dimensions of the acoustically treated enclosure are 8 ft. high by 12 ft. by 11.2 ft. The chamber walls are lined with fiberglass 8 inches thick and flat on the inside, i.e., no anechoic wedges. The entire anechoic chamber is housed inside of a room whose outer walls are lined with lead sheets in order to reduce background noise in the chamber.

The flow facility provides the conditions necessary to obtain specific data relating to various acoustic, flow, and blade parameters involved. The test rotor is being used to generate the turbulence interaction noise under investigation. The auxiliary axial flow fan is used to operate the test rotor at off-design conditions.

Rotor Characteristics

This section outlines the characteristics of the rotor which is employed in the noise facility. The hub-to-tip ratio of the rotor blades is 0.482. The tip diameter of the rotor is 6.90 inches, and the hub diameter is 3.44 inches so that the blade span is 1.73 inches. The chord at 0.75 tip radius is 1.61 in. and the stagger angle at 0.75 tip radius is 0.72 radians. The number of blades on the rotor is variable so that the effects of space-to-chord ratio can be investigated. Rotor blade numbers of 17 and 10 will be tested.

The design advance ratio of the rotor is 2.35. The range of steady axial velocities at the rotor inlet is from 90 to 130 ft./sec. The range of rotor RPM is from 3600 to 5500. The design lift coefficient of the rotor blades is 0.45. The design flow coefficient is 0.75.

Generation of Turbulence

Current investigations are concerned with the noise generated by the rotor blades due to operating in the turbulence of the upstream wakes of struts. The flow velocities past the struts are being maintained so that operation is above critical Reynolds number. The capability exists to change the axial location of the struts, so that the effects of this variation can be investigated. The struts traverse the entire span of the annulus in which the rotor operates.

In addition, investigations are being made of the noise generated by the rotor blades due to operating in a fully developed turbulent boundary layer. The turbulent boundary layer is being generated by artificially roughening a section of the hub upstream of the rotor blade row. The effects of varying the boundary layer thickness on the rotor radiated sound will be investigated. A detailed experimental investigation of the turbulent characteristics of the boundary layers will be made.

EXPERIMENTAL PROGRAM

Previous investigations (Refs. 1-7), both theoretical and experimental, have concentrated on the noise generated due to a blade row operating in a homogeneous, isotropic turbulent inflow. The present program is concerned with the noise generated due to a blade row operating in various non-homogeneous, nonisotropic turbulent inflows, which is the condition existing on typical underwater vehicles.

Three different types of turbulent inflows are considered. The first is that due to the turbulent wakes shed by struts located upstream of the propulsor. The second is the turbulent boundary layer on the hull of the vehicle which is ingested by the propulsor. The third is the secondary flow which is generated at the roots of the struts.

(a) Wake Turbulence:

In a practical case, the rotor is preceded by inlet guide vanes, control surfaces, or support struts. These upstream struts shed wakes which are turbulent, which in combination with the turbulence in the free-stream produce a non-homogeneous, nonisotropic turbulent flow field at the rotor inlet.

Four struts will be placed upstream of the rotor. In this way, various non-homogeneous, nonisotropic turbulent fields can be generated at the rotor inlet. The radiated sound spectra due to the rotor operating in these various turbulent fields will be measured and compared so that fundamental information on the effects of non-homogeneous and nonisotropic turbulent fields on the rotor radiated sound might be obtained. In addition, comparisons with spectra as predicted by analysis which includes the effects of non-homogeneous and non-isotropic turbulence will be made. The parameters to be studied in this program are: turbulence intensity, turbulence integral length scale, wake/blade spacing and flow coefficient.

(b) Boundary Layer Turbulence:

Aerodynamic and acoustic measurements are being carried out with a thick axisymmetric boundary layer at the inlet. The boundary layer is being generated by artificially roughening the walls. The parameters to be studied are: inlet boundary layer thickness, turbulence intensity profile (spanwise) parameter, turbulence intensity, length scale and spectrum, and flow coefficient. The facility will be operated at Reynolds numbers (based on control surface chord length and upstream velocity) above the critical value.

(c) Secondary Flow:

Experiments (a) and (b) will be combined to produce not only the turbulence flow field, but also the secondary flow that is generated by the gradient in the upstream mean velocity and guide vanes (or control surfaces). The parameters to be investigated in this program are: strength of secondary vorticity and the inlet boundary layer thickness.

Determination of Turbulent Flow Fields

In order to understand the relationship between the important characteristics of the turbulent inflow and the radiated noise, the characteristics of each type of turbulence must be measured. The important characteristics of the turbulent inflow for the rotor noise problem are the intensities, spectra, length scales. Measurements of the appropriate components of the fluctuating velocity field will be made using a hot-wire anemometer system.

Since fluctuations in the radial component of velocity will produce no pressure fluctuations on the rotor blades, this component will not be determined for the wake turbulence and boundary layer turbulence to be investigated. Consequently, for these types of turbulent flows, X-array hot-wire anemometer probes will be used to obtain the necessary measurements.

It is felt, however, that for secondary flow field investigations, the characteristics of the turbulent fluctuations in all three coordinate directions should be obtained. This should be done because the basic structure of this type of secondary flow field has not been previously investigated. To accomplish this, triple sensor hot-wire probes will be used to obtain the necessary measurements.

The rotor blades operate in two different types of fluctuating velocity fields; one due to the turbulent fluctuations and the other due to the blades passing through spatial variations in the steady velocity field. These spatial variations are due, for instance, to the mean velocity deficit in the wake of a strut or control surface. Due to operation in these spatial variations of steady velocity, the rotor blades will experience a time-dependent lift which will result in radiated sound. A determination of the axial component of the steady velocity field at the rotor inlet will be made for each type of turbulent flow field being investigated.

Rotor Parameters

The radiated noise from a rotating blade row is a function of a number of rotor parameters. Rotor blade tip velocity, flow coefficient, and blade space-to-chord ratio are the parameters to be considered in this investigation. The noise generated is a function of the flow coefficient (inlet velocity/blade speed). The range of flow coefficients will be determined, based on the yet to be determined stall conditions of the rotor blades, for each type of turbulent inflow.

The time-dependent lift developed by the rotor blades is a function of the space-to-chord (s/c) ratio of the rotor. Consequently, the radiated noise of the rotor is also a function of the rotor s/c ratio. Two rotors having different blade numbers, i.e., 17 and 10, will be used to investigate the effects of s/c ratio. The 17-bladed rotor has an s/c ratio of about 0.6 and the 10-bladed rotor an s/c ratio of about 1.0 based on mid-span values.

Radiated Noise

The noise generated by the blade row due to operation in each type of turbulent inflow will be measured. Both near field and far field sound measurements will be made. Far field sound measurements will be made within the anechoic chamber. The near field measurements are made with a flush mounted microphone in the wall of the facility, outside the anechoic chamber. For each turbulent inflow condition and rotor operating condition of interest the frequency spectrum of the sound pressure level will be measured at an appropriate aspect angle. In addition, the directivity of the radiated sound at frequencies of interest will be determined.

MEASUREMENTS AND DISCUSSION OF RESULTS

The following acoustic and aerodynamic measurements have been completed for a turbulent boundary layer inflow.

(1) Inlet velocity and turbulent intensity profiles at two flow coefficients (axial velocity/blade tip speed) $\phi = 1.03$ and 0.75. This corresponds to inlet mean axial velocities of 167 ft/sec and 123 ft/sec respectively. $\phi = 0.75$ is the design flow coefficient.

(2) Near field [illegible] far field noise measurements at three flow coefficients, $\phi = 1.03, 0.871, 0.75$, (corresponding to free stream axial velocities of 168, 142, and 123 ft/sec, respectively). The measurements were taken with and without a grid at the inlet (as shown in Figure 2). The grid used in this experiment has a mesh size of 1.125 inches and a rod diameter of 0.219 inches.

Flow Data

The flow measurements were carried out with a hot-film sensor about two chords upstream from the rotor as shown in Figure 2. The first set of data (Figure 3) at 168 ft/sec was taken with a single sensor probe. The second set was taken with an "x" configuration hot-film probe. Hence, the turbulence data plotted in Figure 3 for $u_c = 168$ ft/sec is the resultant $\overline{(u')^2 + (w')^2}/U$ where u' is the axial, w' is the tangential component of turbulence intensity, and U is the local mean axial velocity and u_c is the velocity at mid-radius. The spectrum of turbulence was measured by passing the hot-film anemometer signal through a narrow band analyzer.

The data plotted in Figure 3 indicate that the flow is axisymmetric and the boundary layer thickness is 0.4 inches at the hub and 0.45 inches at an annulus wall. The turbulence intensity profile is typical of boundary layer flows.

The second set of data plotted in Figure 3 was taken at a flow coefficient equal to 0.75 with a two sensor hot-film probe. The data shows a decrease in boundary layer thickness to 0.3 at the hub and to 0.35 at the annulus wall. The turbulence intensity in the axial and tantential directions are nearly equal in magnitude as well as having the same distribution from hub to tip.

Acoustic Data

Acoustic measurements were carried out at two locations, called here the near field and the far field. The near-field measurements were taken at the same location as the flow measurements but with the microphone mounted flush to the inner surface of the annulus wall. The far-field measurements were performed inside the anechoic chamber 4.35 duct diameters (30 inches) upstream of the propulsor inlet. The exact locations are shown in Figure 2. All sound measurements were done with a 1/4-inch microphone whose signal was passed through a 10 Hz bandwidth filter and made into a permanent record by a graphic level recorder.

The spectrum of noise level for the flow coefficient of 1.03 is shown in Figure 4. It is quite evident that the ambient noise level and the background noise level with auxiliary equipment operating are well below that of the propulsor itself (greater than 10 db at nearly all frequencies). Hence, the rotor noise spectrum is influenced little by background noise levels. The blade passing frequency (BPF) tone occurs at 1540 Hz at a level of 79 db ref 2×10^{-5} N/M^2. The second harmonic at 3080 Hz is much lower, 70 db, while the third harmonic at 4620 Hz disappears completely into the broadband noise.

Figure 5 shows the spectrum of noise level at a flow coefficient of 0.75 with and without the grid. With the grid, the tone at BPF is 4 dB below the no grid condition in the near field and 6 db below the no grid condition in the far field. The 2 db difference is due to the fact that the noise levels are fluctuating and these are instantaneous level recordings. A similar phenomenon is evident for the second harmonics as well. The reason for the decrease in BPF tone levels with the grid are not clear at this time. It is believed to be caused by a change in tangential length scales caused by the presence of the grid. Additional flow measurements are needed to confirm this phenomena.

Early sound measurements made at different flow coefficients indicate no change in the level of the BPF tone with variation in flow coefficient. Variations in the flow coefficient correspond to changes in steady blade loading. As is indicated in Figure 6, changes in blade loading affect the number of higher harmonics present and possibly the broadband noise levels. The change in broadband noise level could be due solely to turbulent noise of the airflow itself.

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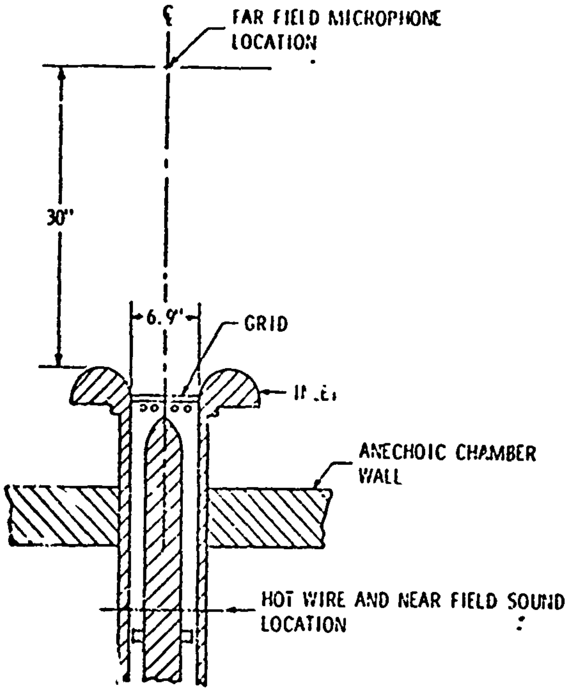

Figure 2: Plan View Showing Hot Film and Microphone Locations

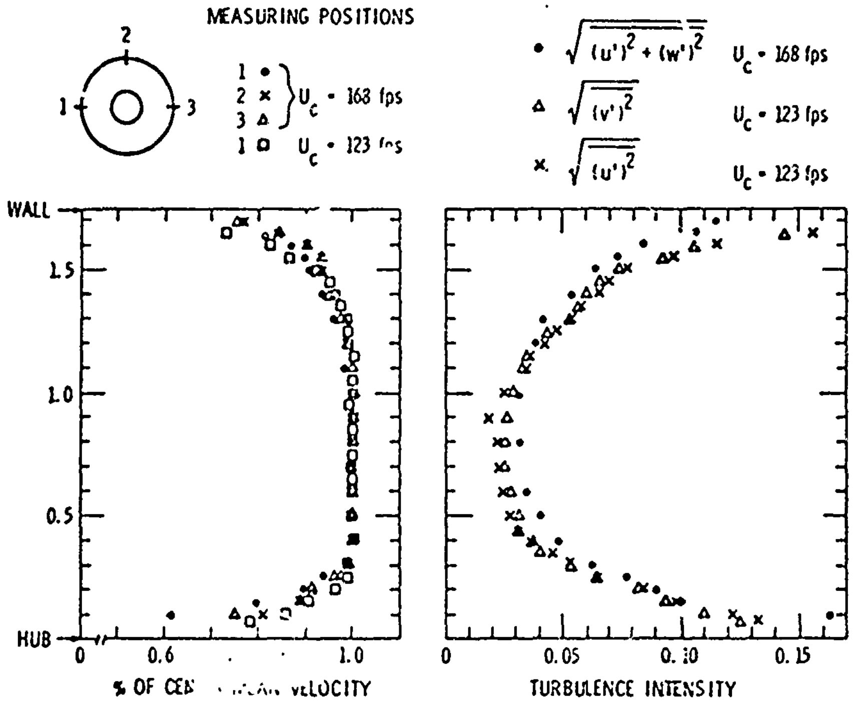

Figure 3: Mean and Turbulent Flow Characteristics Upstream of Rotor U_C = 168 ft/sec, and U_C = 123 ft/sec; No Grid

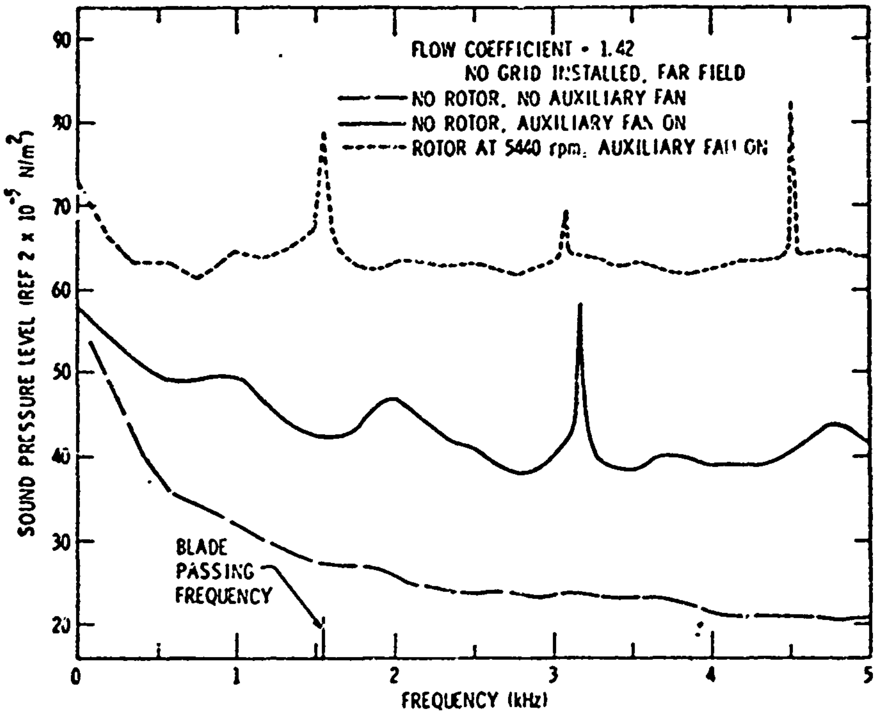

Figure 4: Rotor Noise and Background Levels
U_c = 168 ft/sec (ϕ = 1.03)

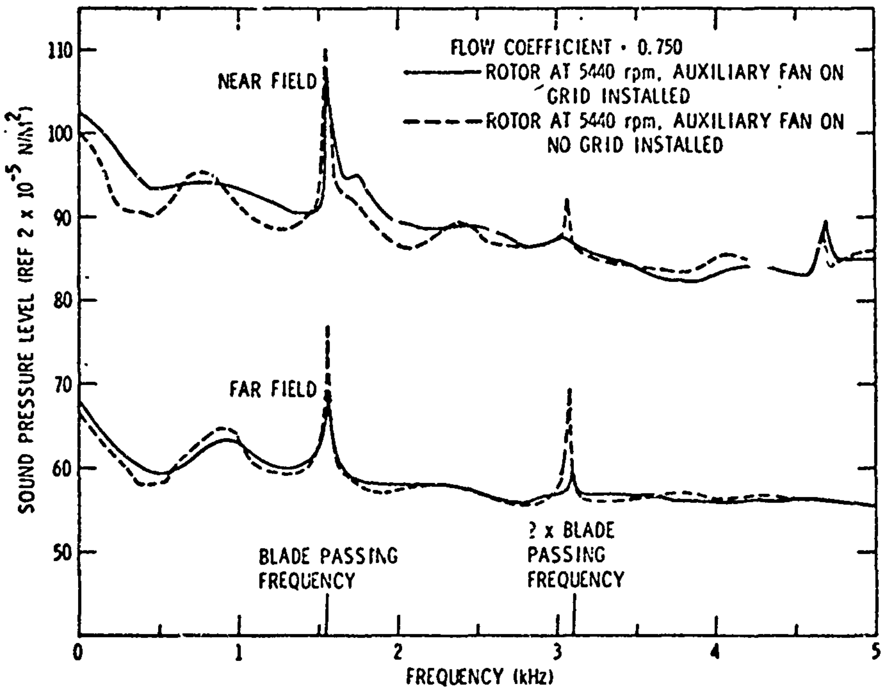

Figure 5: Comparison of Noise Spectra With and Without Grid ϕ = 0.75 U_c = 123 ft/sec

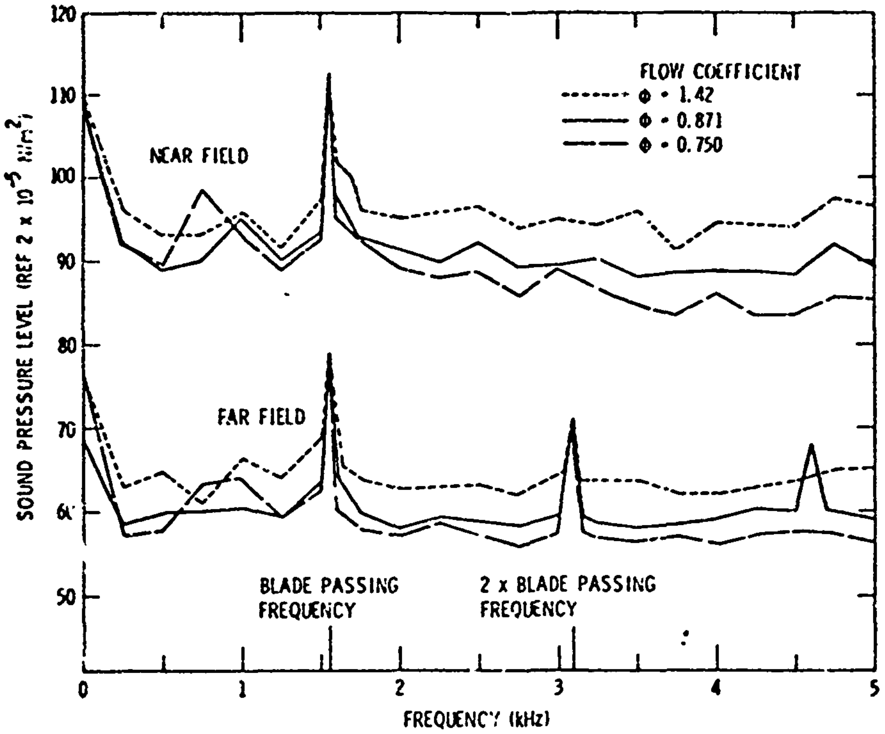

Figure 6: Comparison of Noise Spectra at Different Flow Coefficients