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UNSTEADY FLOW DISTORTION PAST BLADES:  
SOURCES OF NOISE GENERATION IN ROTATING FLOWS

ONR GRANT N00014-89-J-1799

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# UNSTEADY FLOW DISTORTION PAST BLADES:

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## UNSTEADY FLOW DISTORTION PAST BLADES: OBJECTIVES

### *GENERAL*

- DETERMINE FLOW STRUCTURE AT LEADING- AND TRAILING-EDGES OF BLADING IN TERMS OF VELOCITY GRADIENTS REPRESENTING PRESSURE SOURCES.
- EMPLOY ACTIVE AND PASSIVE CONTROL TECHNIQUES TO MANIPULATE CRUCIAL PHASE SHIFTS OF VORTICITY FIELDS PAST BLADING.

### *DESIGN AND IMPLEMENTATION OF EXPERIMENTAL SYSTEMS*

- GENERIC, CONTROLLED SYSTEMS FOR STUDY OF BASIC CLASSES OF LEADING- AND TRAILING-EDGE INTERACTIONS.
- UNIQUE RADIAL FLOW MACHINE FOR SIMULTANEOUS ACTIVE CONTROL AND FLOW VISUALIZATION.

### *DEVELOPMENT OF EXPERIMENTAL TECHNIQUES*

- TECHNIQUES FOR QUANTITATIVE BUBBLE AND PARTICLE TRACKING VIA LASER DIAGNOSTICS.
- METHODS OF EVALUATION OF IMAGES VIA LASER INTERROGATION.
- APPROACHES TO TWO- AND THREE-DIMENSIONAL IMAGE CONSTRUCTION.

# UNSTEADY FLOW DISTORTION PAST BLADES: RESEARCH PLAN

## PHASE I

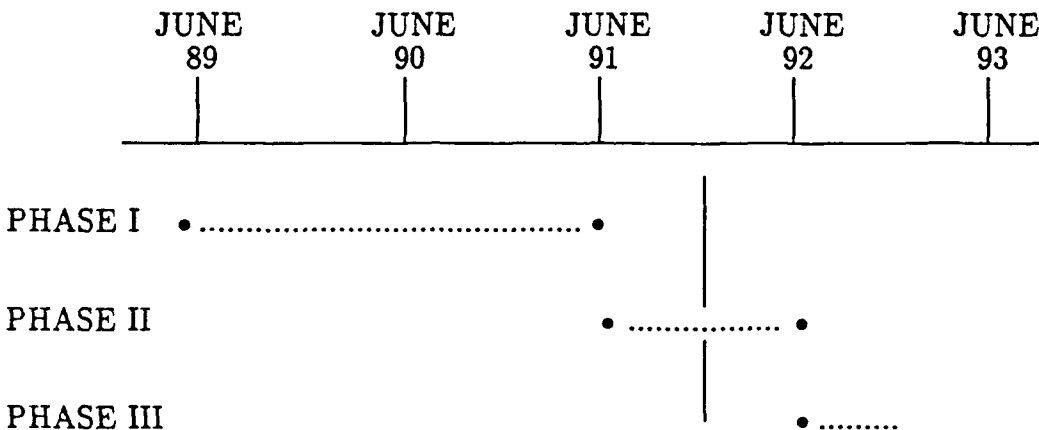
- DESIGN, CONSTRUCTION AND DEVELOPMENT OF:
  - ✓ UNIQUE ROTATING MACHINE FOR VISUAL ACCESS AND ACTIVE CONTROL
  - ✓ CONTROLLER SYSTEMS FOR ROTATING MACHINE
  - ✓ LASER DIAGNOSTIC TECHNIQUES FOR QUANTITATIVE FLOW VISUALIZATION AND INTERPRETATION
- EXPERIMENTAL STUDY OF GENERIC CLASSES OF LEADING-/TRAILING-EDGE INTERACTIONS

## PHASE II

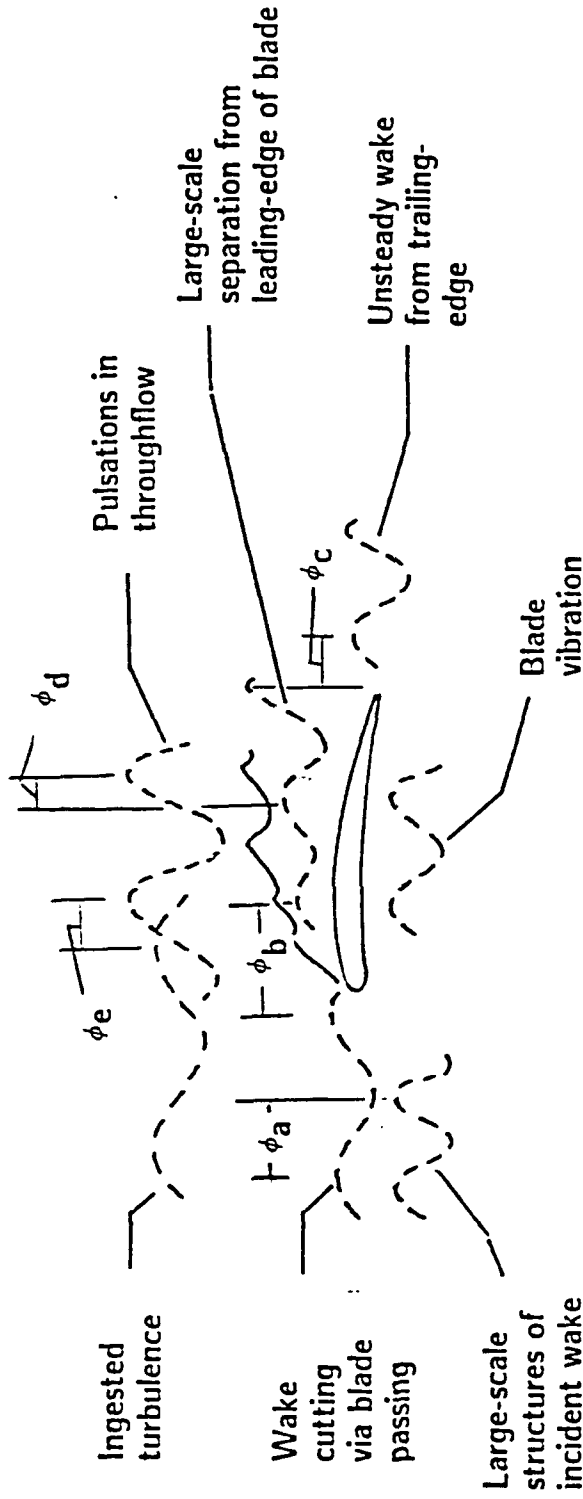
- PRELIMINARY STUDIES OF FLOW STRUCTURE IN ROTATING MACHINE VIA LASER DIAGNOSTICS
- ACTIVE/PASSIVE CONTROL CONCEPTS OF GENERIC EDGE INTERACTIONS

## PHASE III

- ACTIVE CONTROL STUDIES OF FLOW IN ROTATING MACHINE
- CONTROL OF GENERIC EDGE INTERACTIONS



# PRINCIPAL PHYSICAL CONCEPTS



The principal features of this research program involve identification of the elements of unsteady flow structure and their active control by applying disturbances of desired frequency and phase. Proper phase shift  $\phi$  between dynamic events may allow attenuation of unsteady mechanisms of noise generation.

PRINCIPAL MECHANISMS OF FLOW DISTORTION  
RELATED TO NOISE GENERATION: CONCEPTS

I. INTERPRETATIONS OF PRESSURE SOURCE TERMS

$$\begin{aligned}\nabla^2 p &= 2\rho \left\{ \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \right\} \\ &= -\rho \left\{ \nabla \cdot (\underline{\omega} \wedge \underline{V}) + \nabla^2 \left( \frac{1}{2} V^2 \right) \right\} \\ &= -\rho \left\{ \frac{\partial^2 v_i v_j}{\partial x_i \partial x_j} \right\} \quad T_{ij} \approx \rho_0 v_i v_j\end{aligned}$$

II. FAR-FIELD ACOUSTIC PRESSURE DUE TO FLOW DISTORTION IN FREE SPACE

Expressions of (I) serve as source terms in inhomogeneous wave equations. Solve for far-field density or pressure.

III. FAR-FIELD ACOUSTIC PRESSURE DUE TO FLOW DISTORTION ADJACENT TO SURFACE/BODY

(a)  $p(\underline{x}, t)$  via Lighthill's  $T_{ij}$  using deductive theory of surface effects.

(b)  $p(\underline{x}, t) = \frac{-x_i}{4\pi c |\underline{x}|^2} \frac{\partial}{\partial t} F_i$  (Curle, 1955)

$$F_i = \int \rho_0 \nabla X_i(\underline{y}) \cdot (\underline{\omega} \wedge \underline{V})(\underline{y}, t - \frac{|\underline{x}|}{c}) d^3 \underline{y} \quad (\text{Howe, 1989})$$

$$\underline{F} = -\sigma \rho_0 \frac{\partial}{\partial t} \int (\underline{x} \wedge \underline{\omega}) d^3 \underline{x} \quad (\text{Lighthill, 1986})$$

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**PARTICLE IMAGE VELOCIMETRY (PIV)  
VIA LASER DIAGNOSTIC METHODS**

***GOALS***

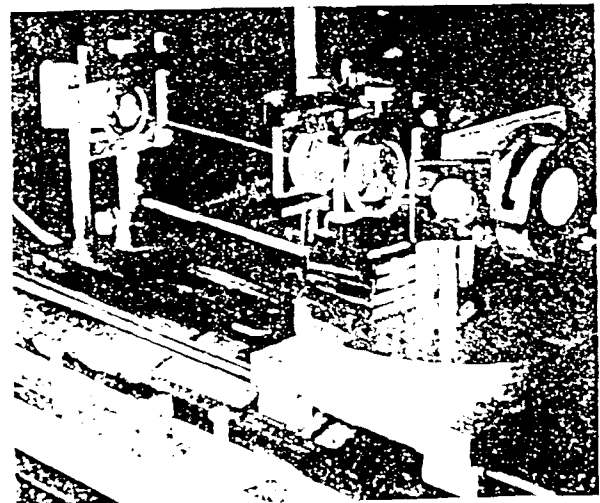
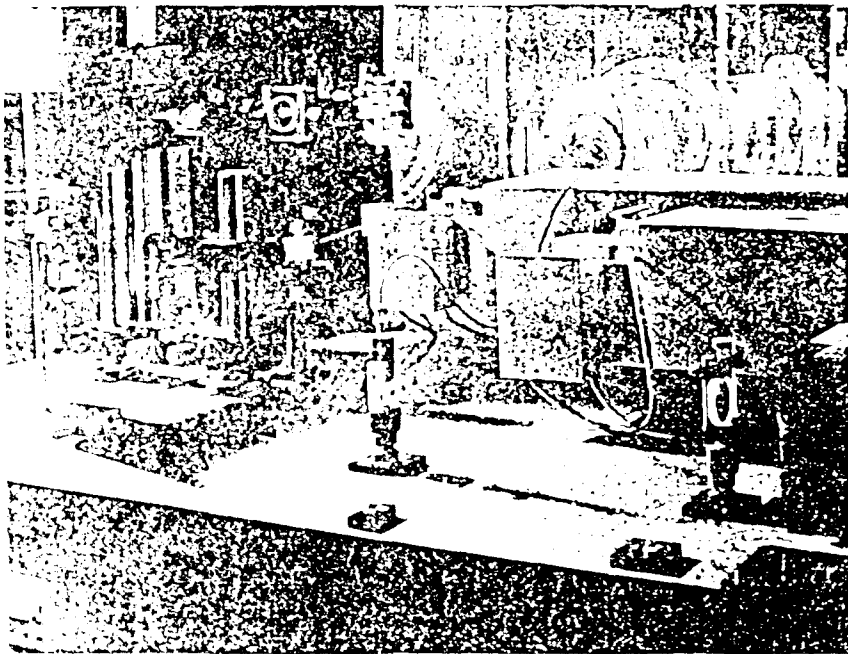
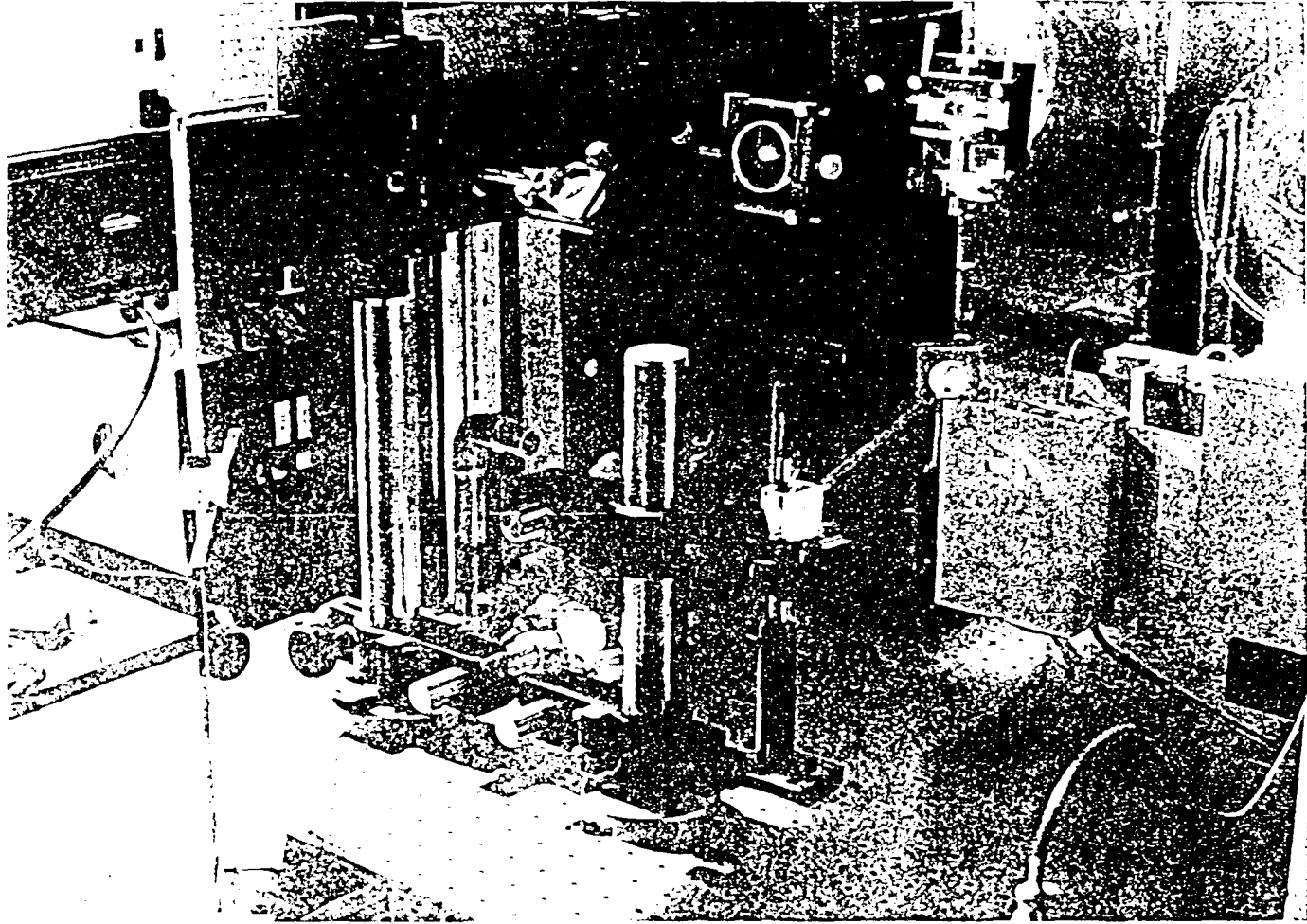
- INSTANTANEOUS VELOCITY FIELD ACROSS PLANE OF FLOW AT ARBITRARY PHASE OF ROTATING BLADE SYSTEM
- HIGH RESOLUTION MEASUREMENTS VIA SMALL PARTICLE DISPLACEMENTS ( $\sim 10^2 \mu\text{m}$ ) AND MINIMAL INTERPOLATION.
- CHARACTERIZATION OF VELOCITY GRADIENTS REQUIRED FOR CALCULATION OF VORTICITY AND PRESSURE SOURCES

***SYSTEM DEVELOPMENT***

- MINIMIZATION OF PARTICLE SIZE AND OPTIMIZATION OF IMAGE FOCUSING VIA PROPER COMBINATION OF LASER SOURCE, CAMERA, LENS SYSTEM
- IMAGE SHIFTING VIA OSCILLATING BIAS MIRROR
  - ✓ PRECLUDE DIRECTIONAL AMBIGUITY
  - ✓ OPTIMIZE PARTICLE DISPLACEMENT AND FRINGE SPACING
- GENERATION OF HIGH-INTENSITY PULSED- AND SCANNED-LASER SHEETS
  - ✓ DUAL-PULSED YAG SYSTEM WITH BEAM COMBINER OPTICS
  - ✓ SINGLE CW SCANNED ARGON-ION SYSTEMS (ACOUSTO-OPTIC AND MIRROR SCANNER)
- OPTICAL SYSTEMS FOR TRANSLATION AND ROTATION OF LASER SHEETS
- INTEGRATED COMPUTER CONTROL OF
 

✓ LASER FIRING	✓ IMAGE SHIFTING
✓ PUMP IMPELLER ROTATION	✓ CAMERA TRIGGERING
✓ PUMP INLET FLOW	✓ EXTERNAL SHUTTERS
- HARDWARE INTERFACING AND SOFTWARE DEVELOPMENT RELATED TO FOREGOING

PARTICLE IMAGE VELOCIMETRY (PIV)  
VIA LASER DIAGNOSTIC METHODS

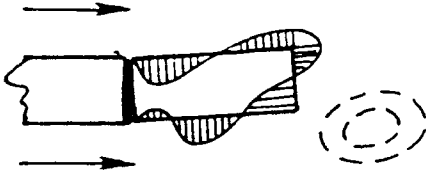


## UNSTEADY FLOW DISTORTION PAST BLADES

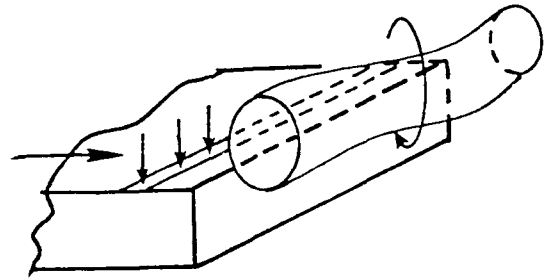
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# GENERIC EDGE/SURFACE INTERACTIONS

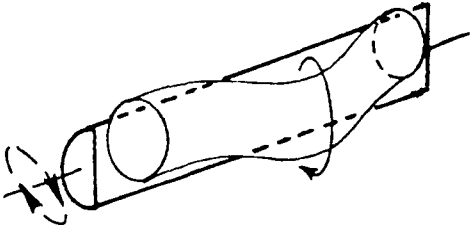
## TRAILING-EDGE INTERACTIONS



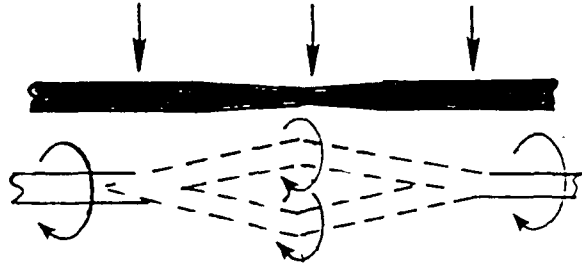
WAKE FROM TRAILING-EDGE UNDERGOING SINUSOIDAL PERTURBATIONS



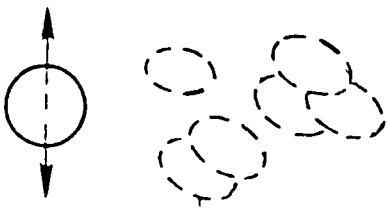
WAKE FROM STATIONARY TRAILING-EDGE WITH BOUNDARY-LAYER SUCTION



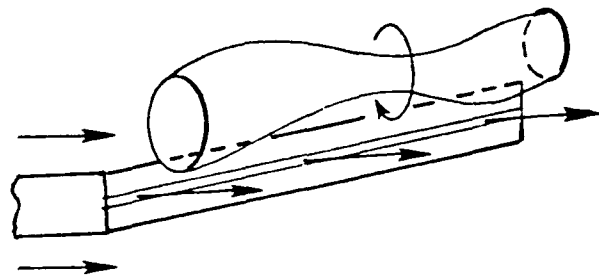
WAKE FROM D-CYLINDER UNDERGOING DUAL MODE EXCITATION



WAKE FROM MILDLY NONUNIFORM CYLINDER PERTURBED SINUSOIDALLY



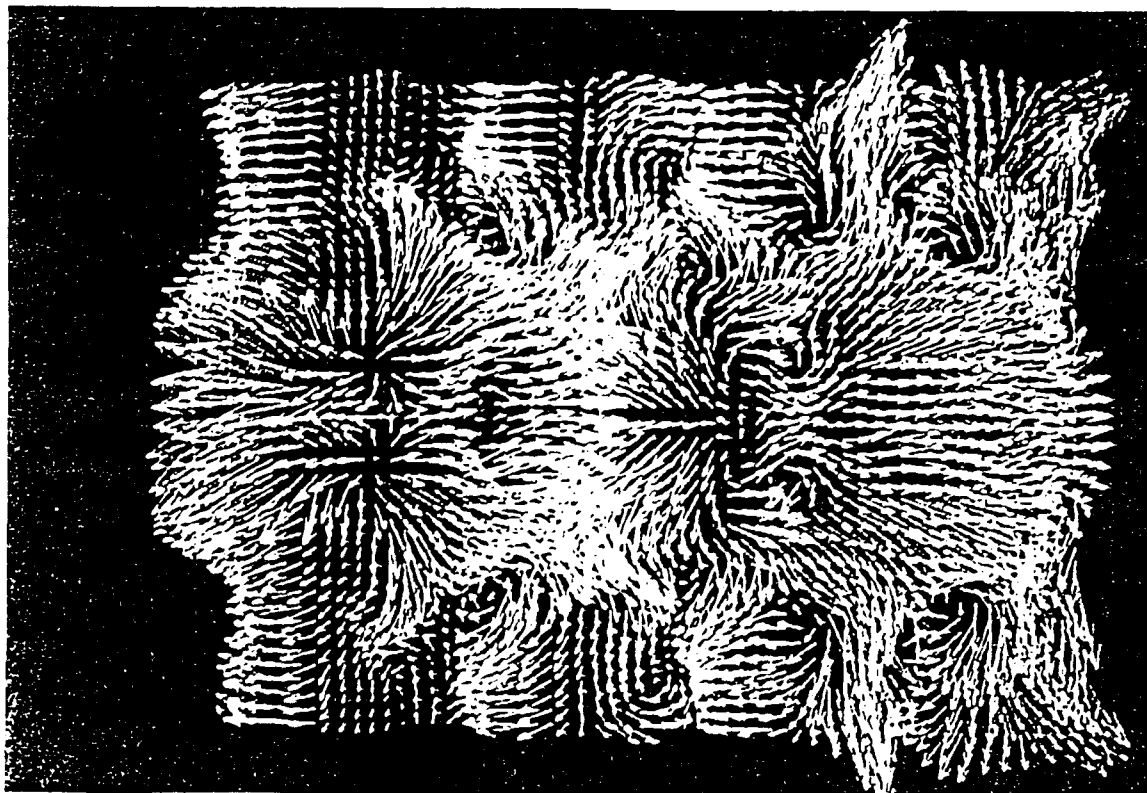
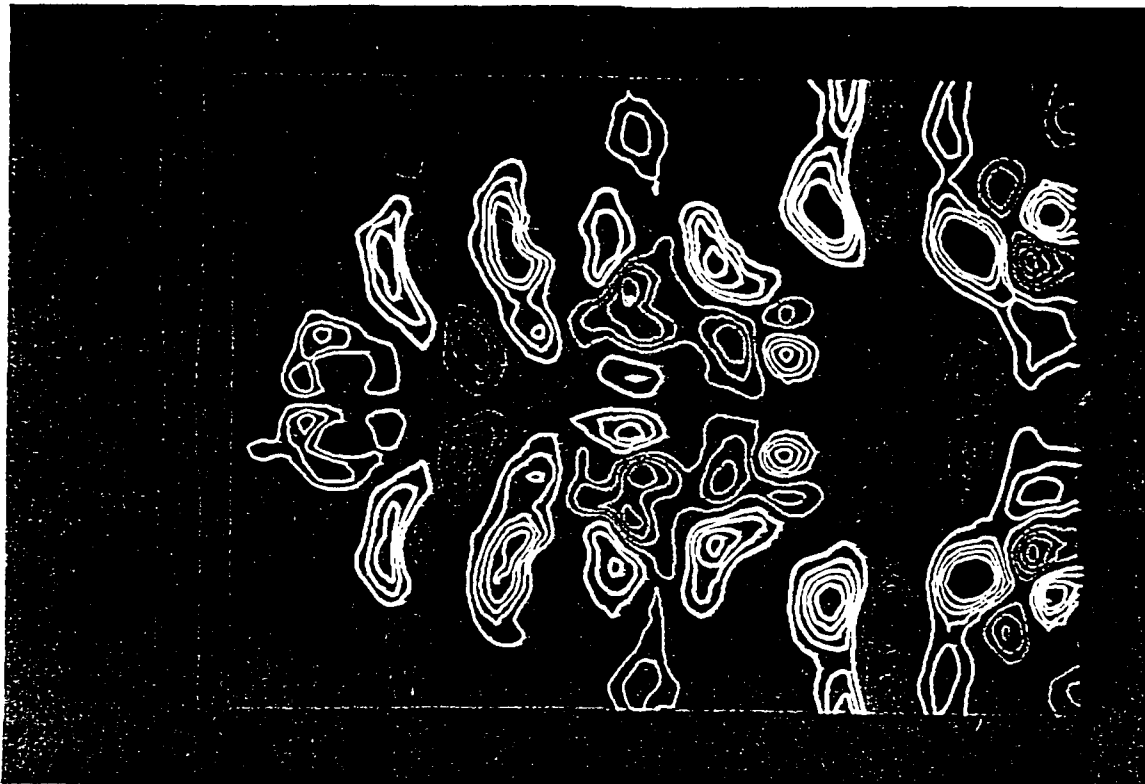
WAKE FROM CYLINDER UNDERGOING AMPLITUDE- AND FREQUENCY-MODULATED EXCITATION



WAKE FROM STATIONARY TRAILING-EDGE WITH BASE BLOWING

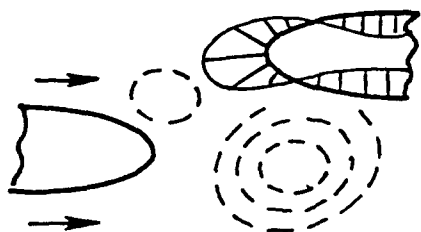
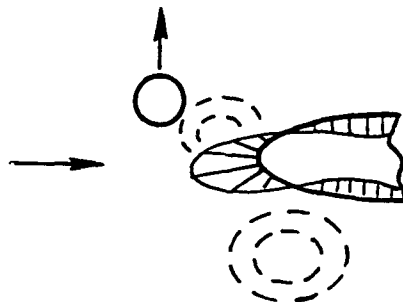
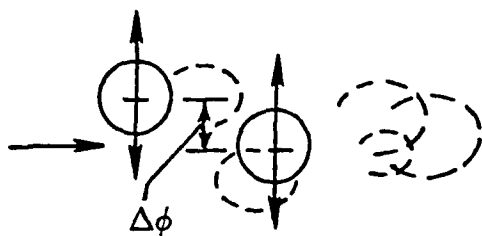
GENERIC EDGE/SURFACE INTERACTIONS

TRAILING-EDGE INTERACTIONS



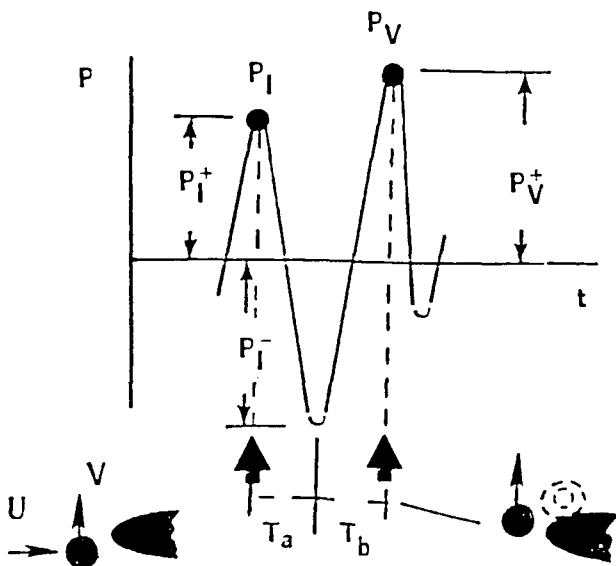
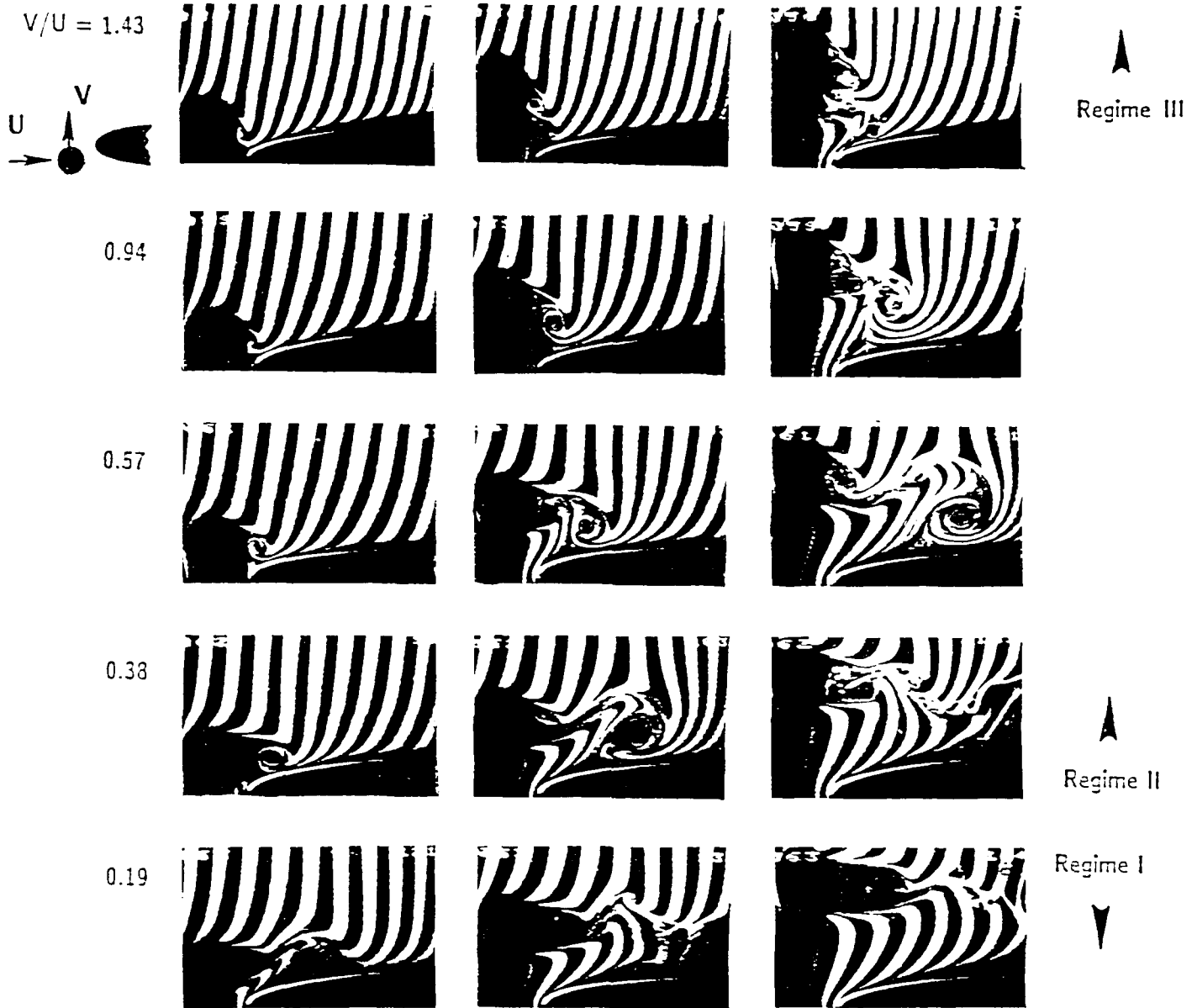
## GENERIC EDGE/SURFACE INTERACTIONS

## LEADING-EDGE INTERACTIONS

WAKE ASYMMETRICALLY INCIDENT  
UPON LEADING-EDGEWAKE FROM GENERATOR  
PAST LEADING-EDGEWAKE-GAP INTERACTIONS IN  
SYSTEM OF OSCILLATING CYLINDERS

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# SIMULATED BLADE-BLADE INTERACTION: DEVELOPMENT OF VORTEX AND PRESSURE FIELDS



CYLINDER TO FREE-STREAM VELOCITY RATIO  $V/U$  DETERMINES RATE OF DEVELOPMENT OF LARGE-SCALE STRUCTURES IN GAP BETWEEN CYLINDER AND ELLIPTICAL LEADING-EDGE.

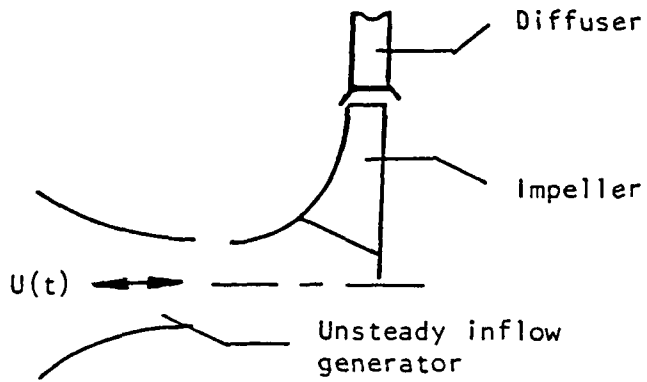
RELATIVE AMPLITUDES OF  $P_I$  (INVISCID) AND  $P_V$  (VORTICITY) PRESSURE PEAKS AND PHASE OF OCCURRENCE OF PEAKS (AT  $T_a$  AND  $T_b$ ) ARE FUNCTIONS OF VELOCITY RATIO  $V/U$  AND DISTANCE ALONG LEADING-EDGE.

## UNSTEADY FLOW DISTORTION PAST BLADES

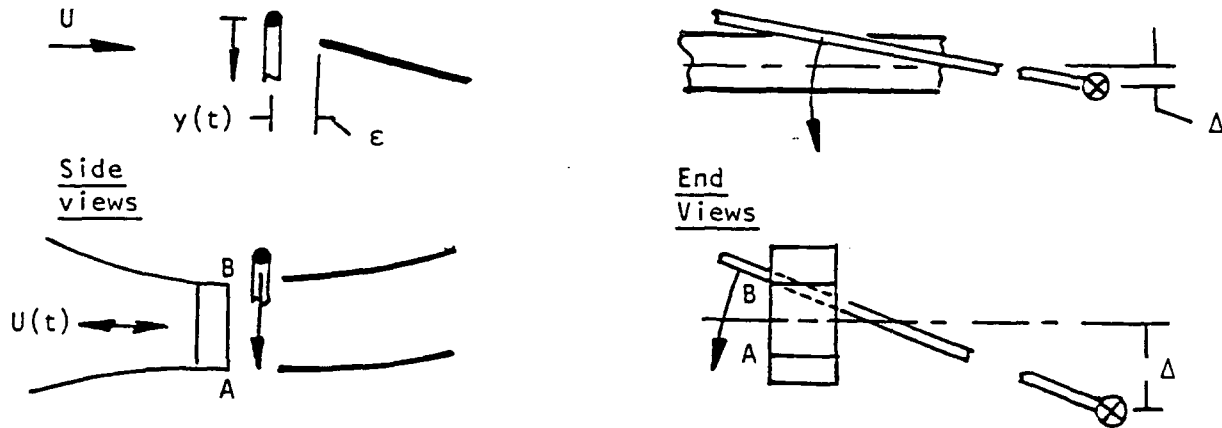
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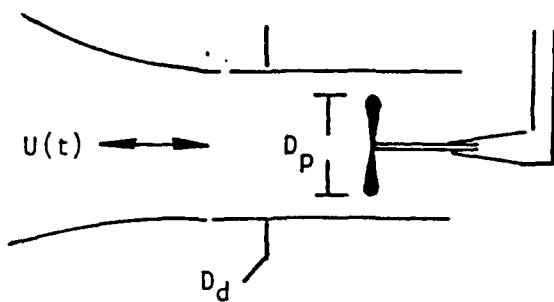
**CONTROLLED PUMP:  
RADIAL FLOW IMPELLER-  
DIFFUSER SYSTEM**



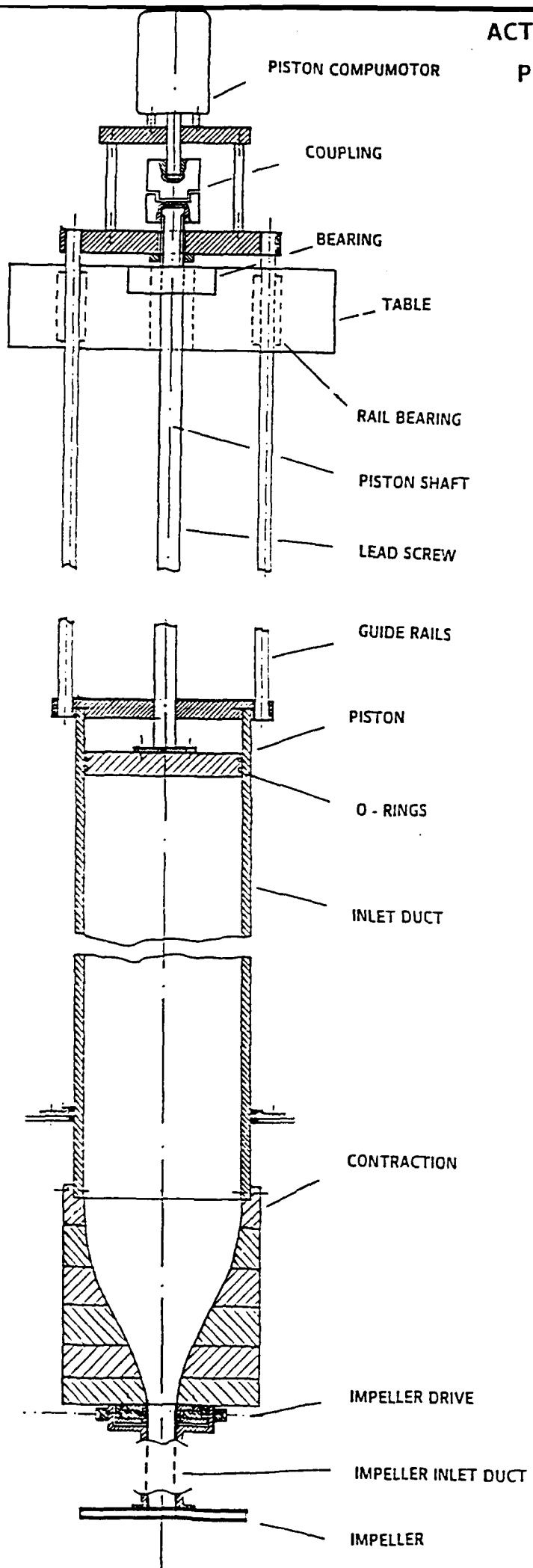
**CONTROLLED WAKE-BLADE INTERACTION SYSTEM (PROJECTED)**



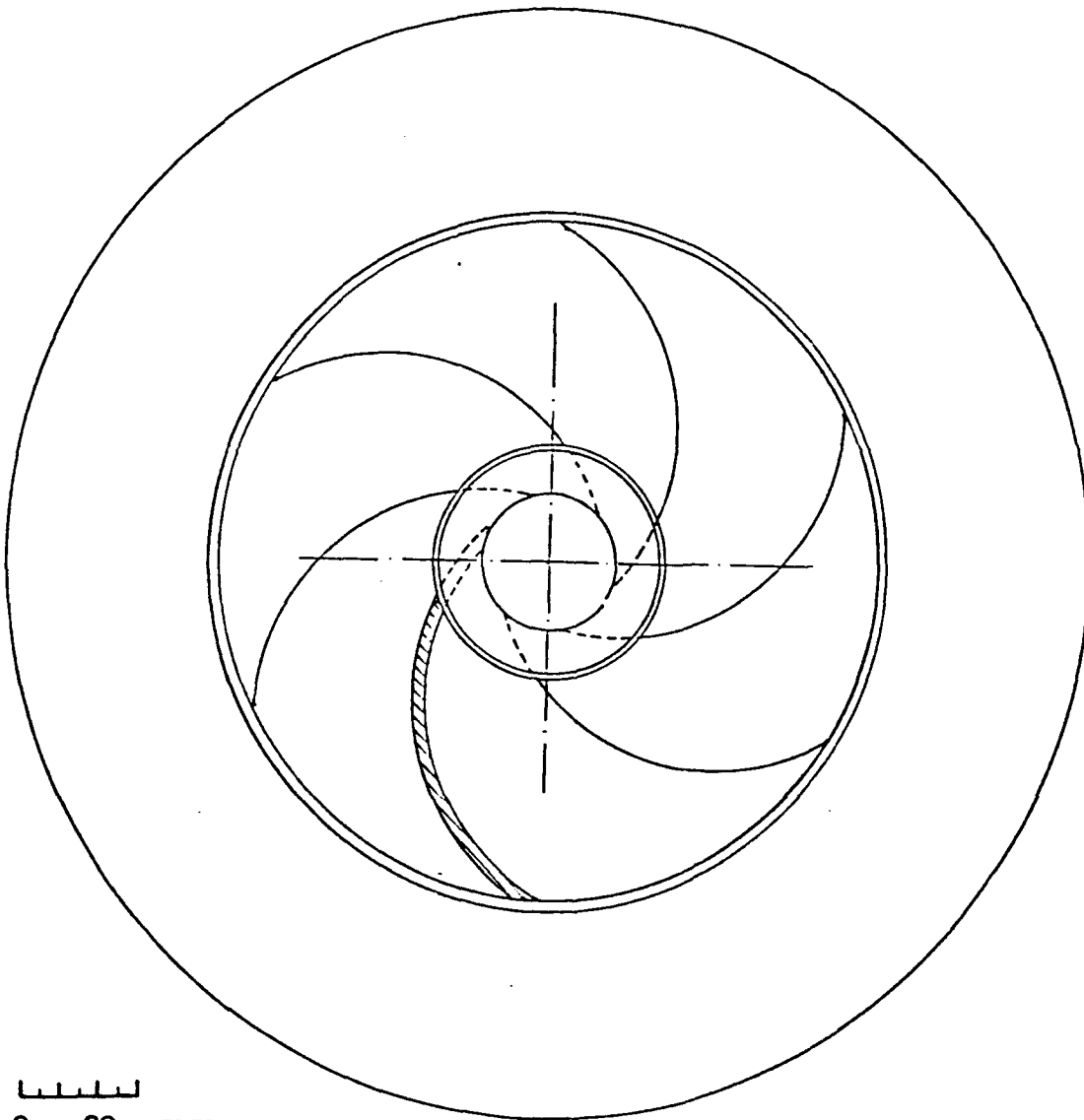
**CONTROLLED AXIAL FLOW  
PROPELLER SYSTEM (PROJECTED)**



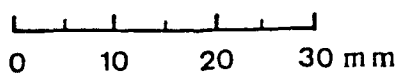
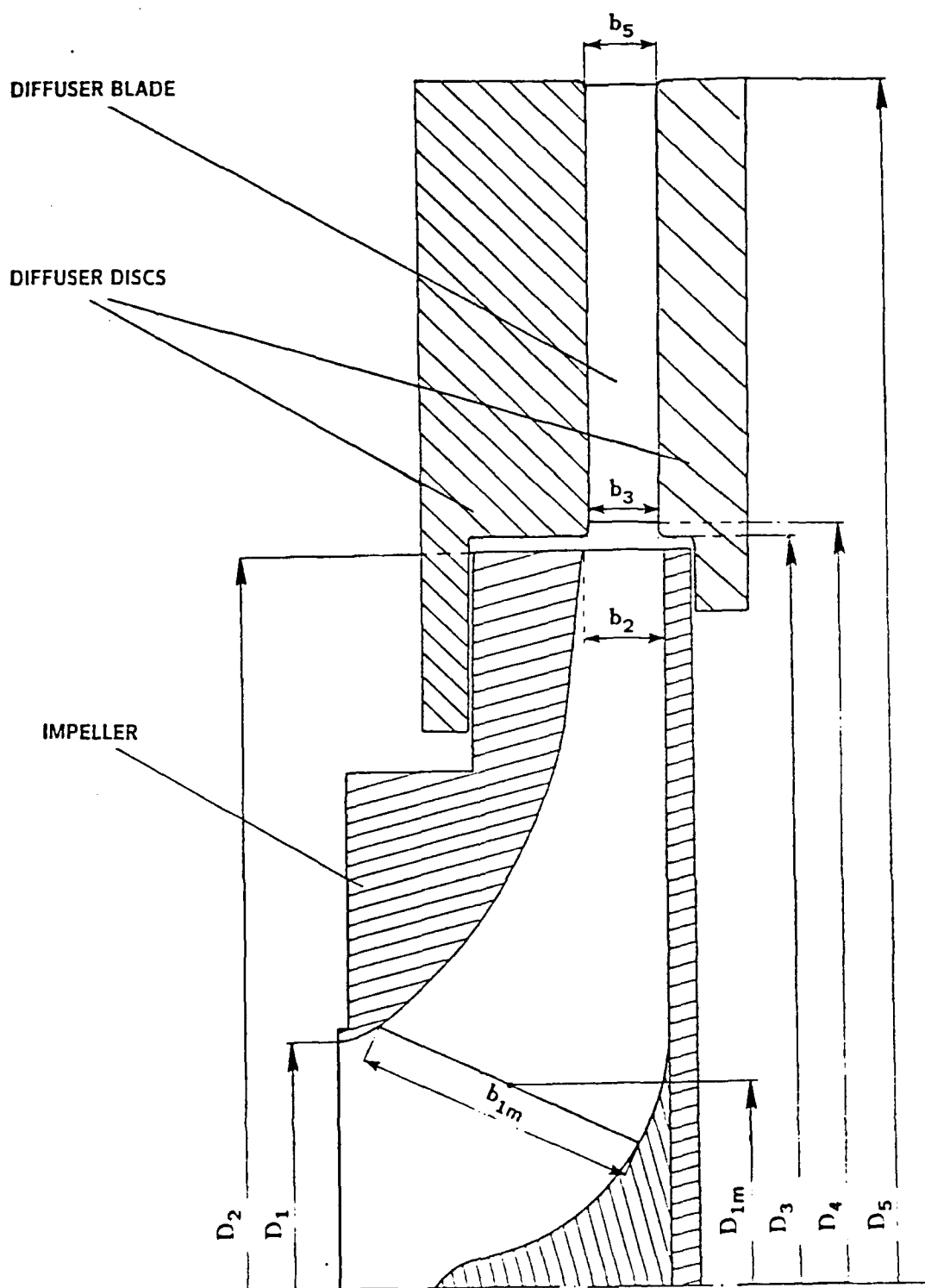
ACTIVELY-CONTROLLED  
PUMPING SYSTEM



## EXPERIMENTAL SYSTEMS

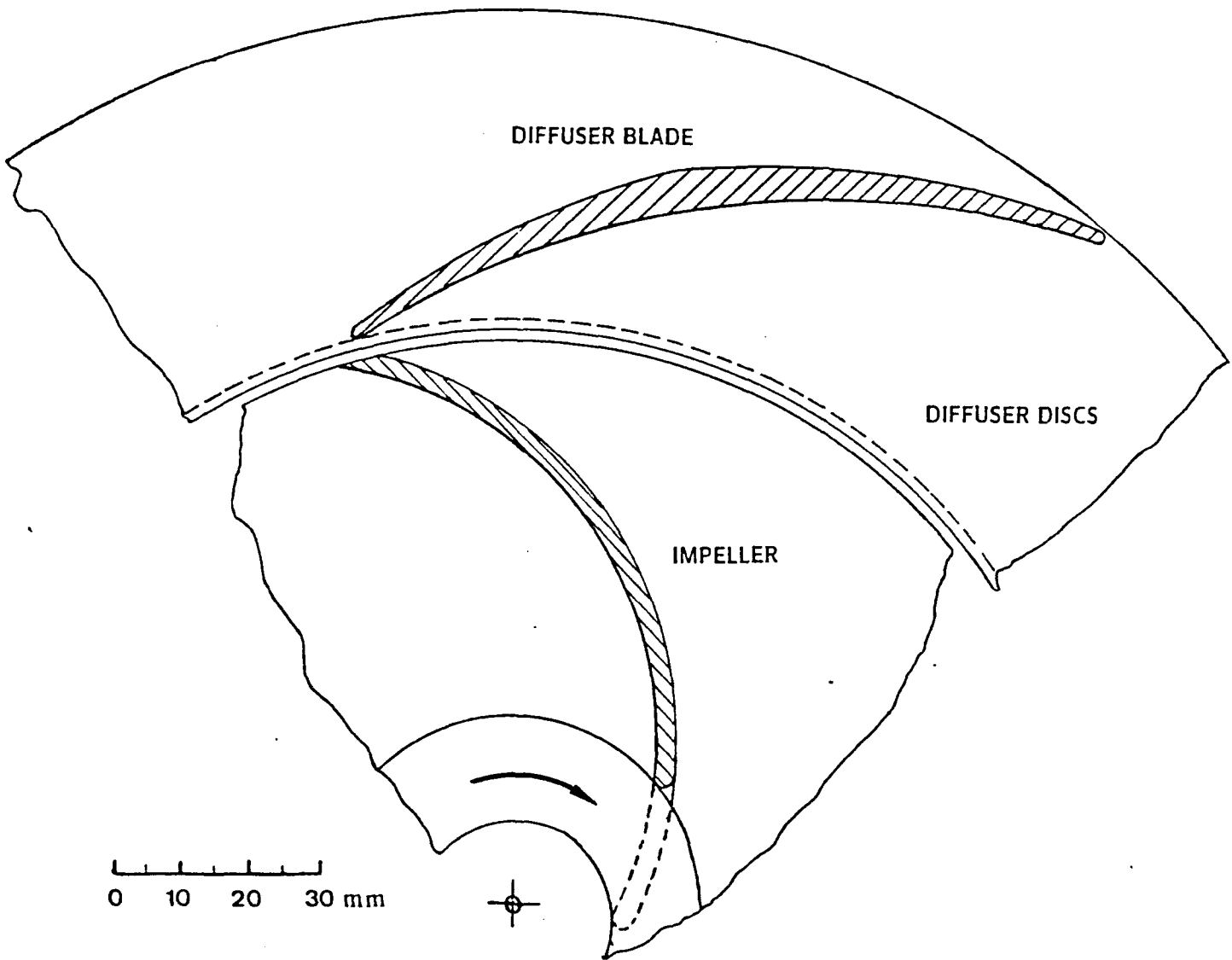
PLAN VIEW OF  
IMPELLER-VANELESS  
DIFFUSER SYSTEM

## EXPERIMENTAL SYSTEMS

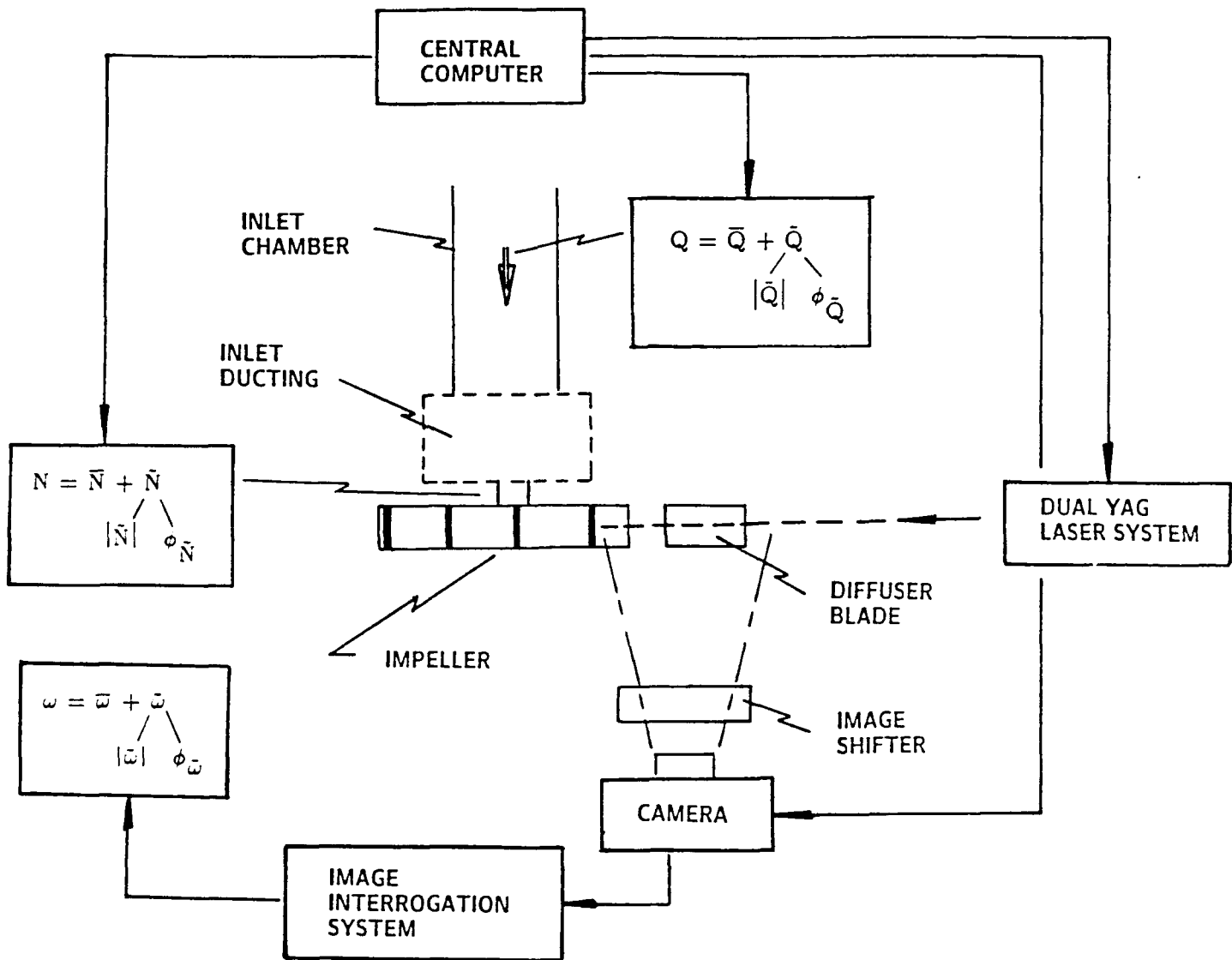
CROSS-SECTIONAL VIEW OF  
IMPELLER-DIFFUSER SYSTEM

### EXPERIMENTAL SYSTEMS

PLAN VIEW OF  
IMPELLER-DIFFUSER  
BLADE SYSTEM



EXPERIMENTAL SYSTEMS: INTEGRATED ACTIVE CONTROL -  
FLOW VISUALIZATION SYSTEM

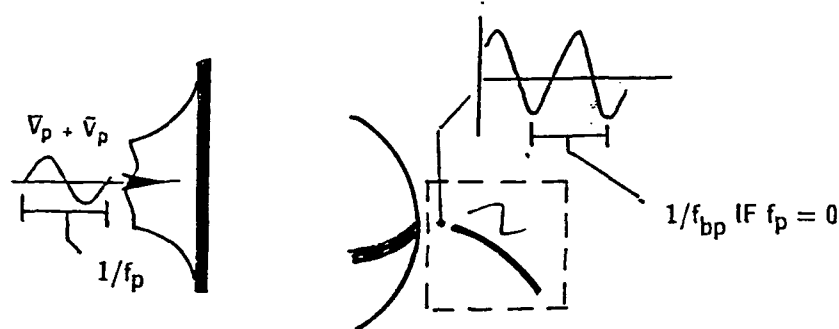


- INLET FLOW  $Q$  AND IMPELLER ROTATION  $N$  HAVE ARBITRARY FUNCTIONAL FORMS AND PHASE SHIFTS.
- CENTRAL COMPUTER CONTROLS FLOW  $Q$ , ROTATION, AND MULTIPLE FIRING OF YAG LASER SYSTEM AND CAMERA SYSTEM.
- CAMERA-IMAGE INTERROGATION SYSTEM GIVES INSTANTANEOUS VELOCITY AND VORTICITY FIELDS.

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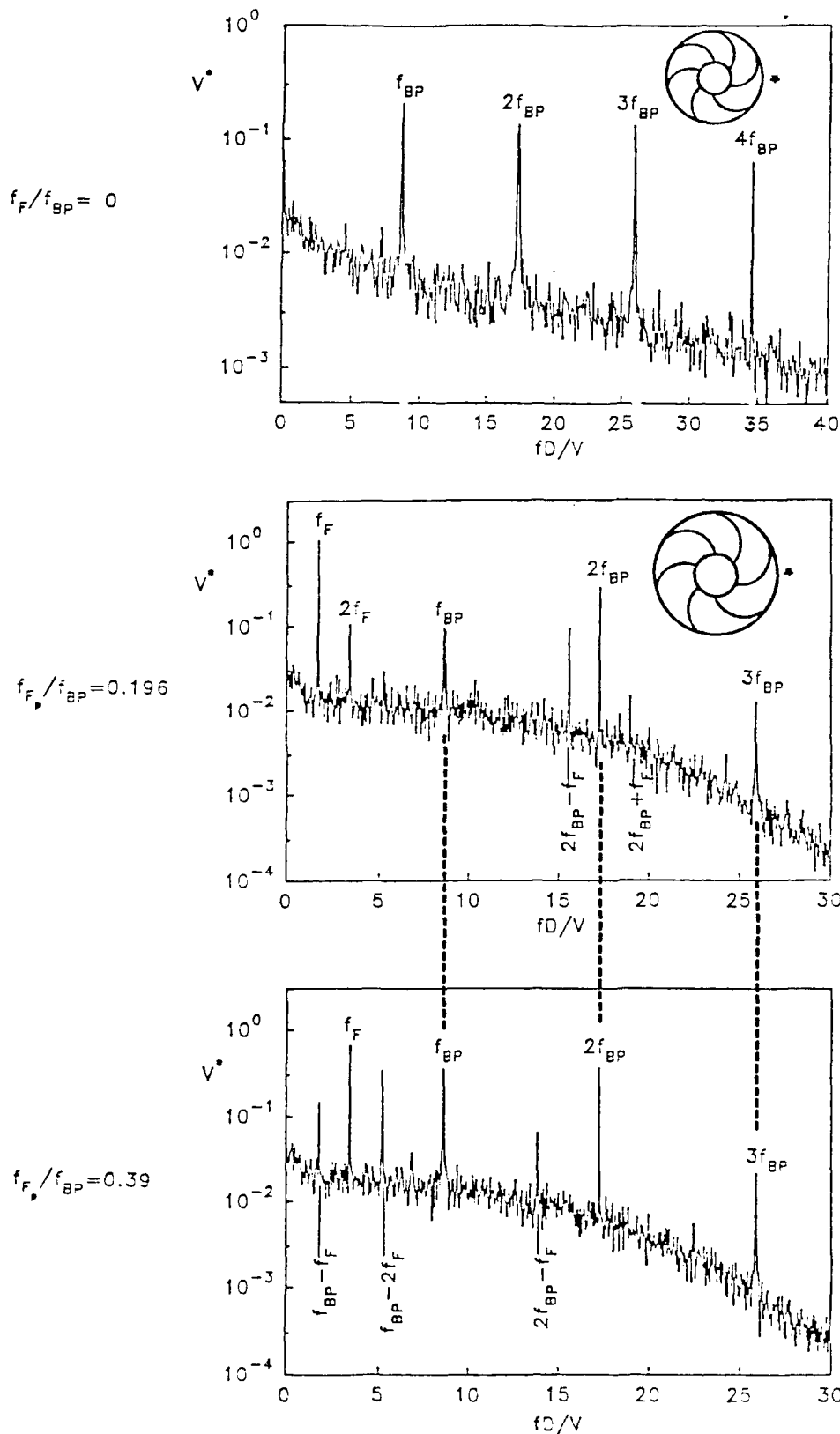
OVERALL RESPONSE TO CONTROLLED EXCITATION:  
GENERATION OF MODULATED SPECTRAL COMPONENTS AND FLOW  
STRUCTURE—HYPOTHESIZED MECHANISMS



- (a) IN ABSENCE OF INFLOW PULSATIONS AT  $f_p$ , FLOW STRUCTURE TENDS TO REPEAT WITH PERIOD  $1/f_{bp}$ .
- (b) IN PRESENCE OF INFLOW PULSATIONS AT  $f_p$ , FLOW STRUCTURE TENDS TO REPEAT AT DIFFERENCE FREQUENCY  $f_p - f_{bp}$  AND ITS NONLINEAR HARMONICS.
- (c) REINFORCEMENT OF THESE COMPONENTS AND GENERATION OF ADDITIONAL DISCRETE COMPONENTS CAN ARISE FROM NONLINEAR INTERACTION BETWEEN  $f_p$  AND  $f_{bp}$  IN BOUNDARY LAYER OR SEPARATING SHEAR LAYER TO GIVE  $nf_p \pm mf_{bp}$ .
- (d) IF INFLOW FORCING HAS AMPLITUDE- OR FREQUENCY-MODULATED FORM, THEN LARGE NUMBER OF SUM AND DIFFERENCE COMPONENTS IS EXPECTED DUE TO MULTIPLE SIDEBAND INTERACTIONS.
- (e) FOREGOING PROCESSES CAN INFLUENCE RATE AT WHICH SPECTRAL BROADENING OCCURS.
- (f) SPECTRAL BROADENING SHOULD BE ENHANCED BY EXISTENCE OF ADVERSE PRESSURE GRADIENT (VANELESS DIFFUSER) OR SEPARATION ZONES (DIFFUSER OR CUTOFF BLADES).

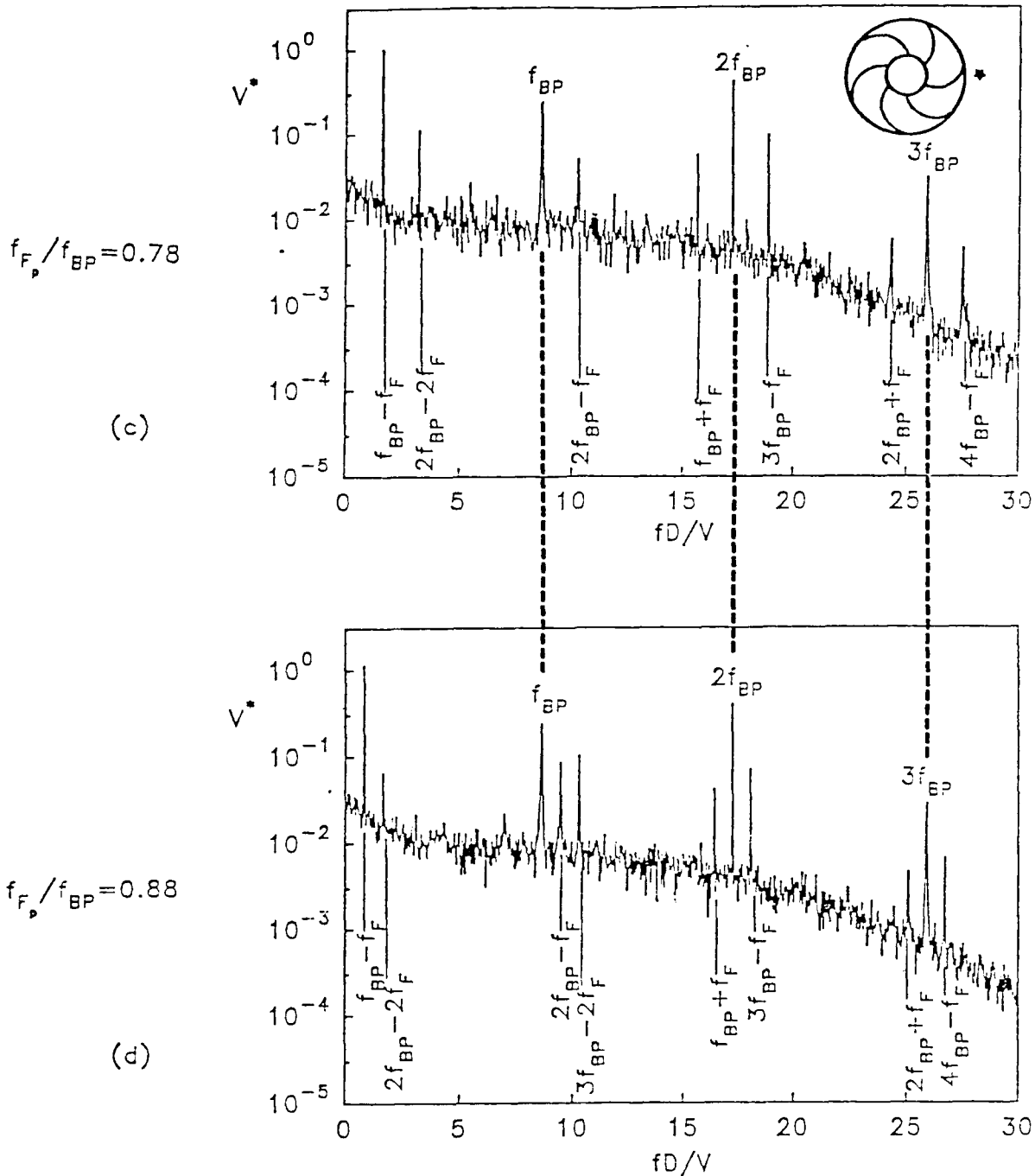


OVERALL RESPONSE TO CONTROLLED EXCITATION: GENERATION OF  
NONLINEAR INTERACTION COMPONENTS

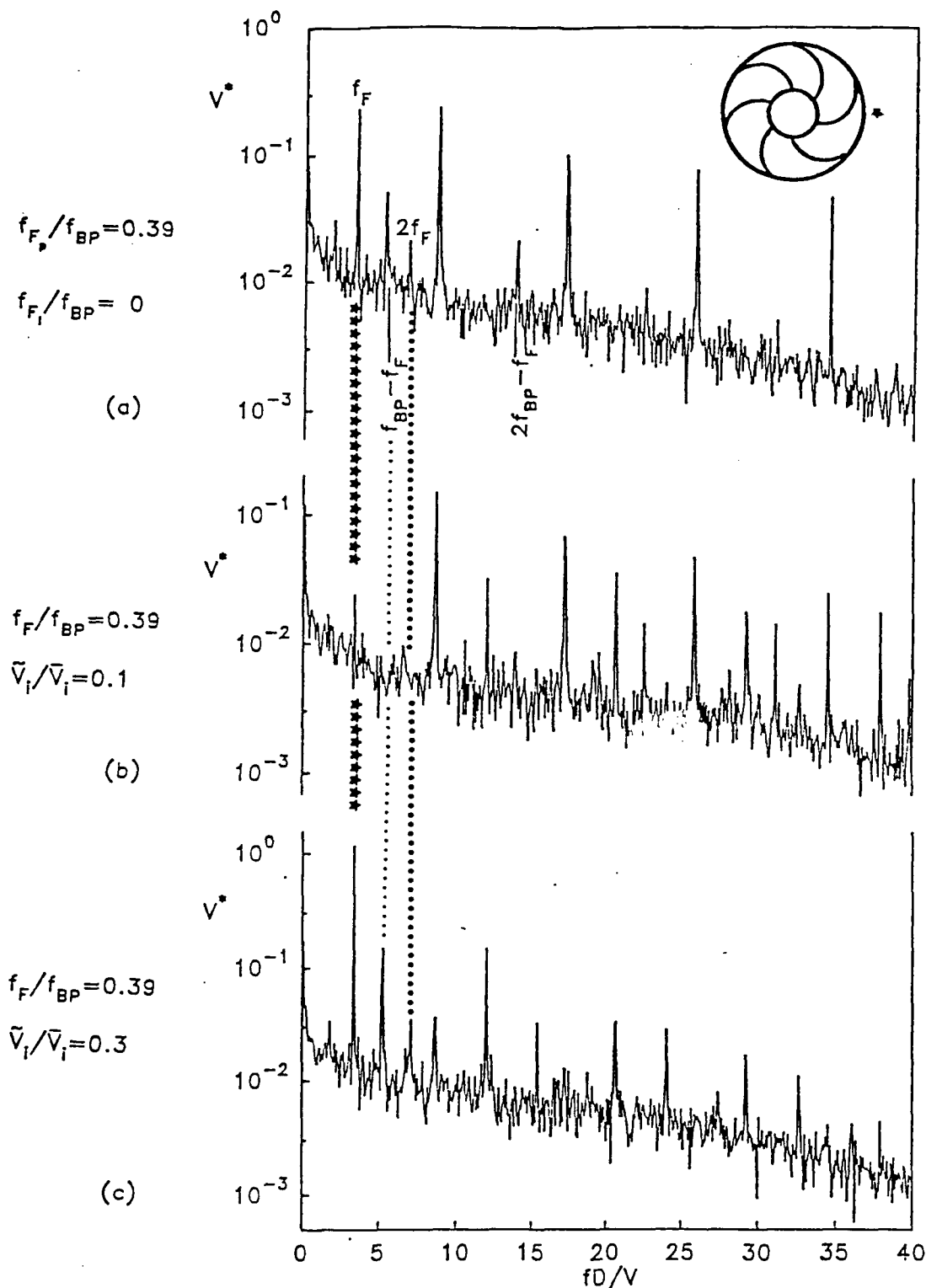


The power spectral density of the velocity fluctuation  $V^*$  is measured at the indicated (\*) location at the exit of the impeller. At a relatively low value of the inflow perturbation frequency  $f_F$ , relative to the blade passing frequency,  $f_{BP}$ , i.e.  $f_F/f_{BP} = 0.196$ , only the first harmonic  $2f_F$ , as well as nonlinear interaction components with  $2f_{BP}$  are present. Increasing the dimensionless inflow perturbation frequency to  $f_F/f_{BP} = 0.39$  produces pronounced sum and difference components between  $f_F$  and  $f_{BP}$ .

# OVERALL RESPONSE TO CONTROLLED EXCITATION: ATTENUATION OF FORCING COMPONENT AND GENERATION OF NONLINEAR INTERACTIONS

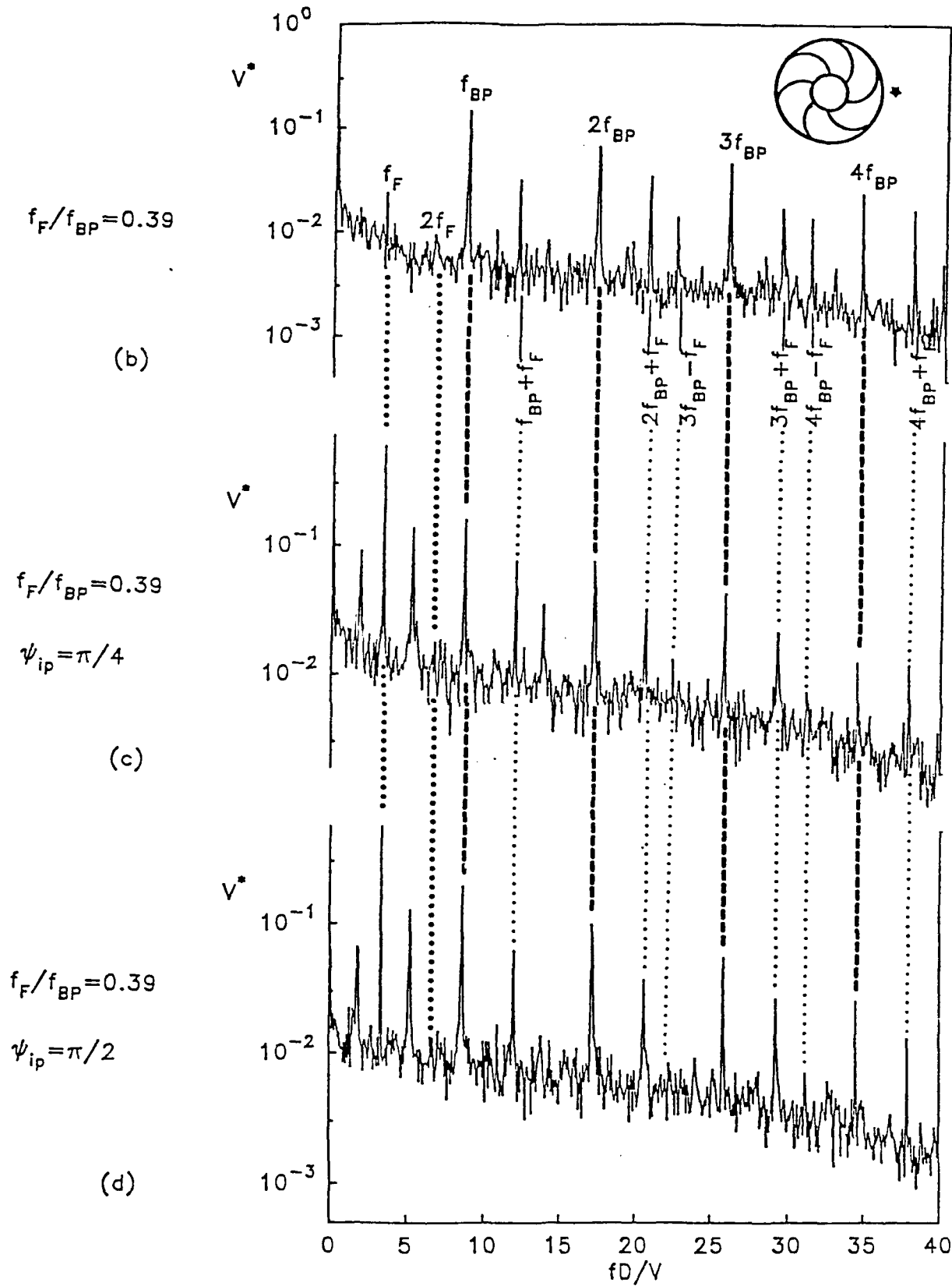


The power spectral density  $V^*$  of the velocity component measured at the indicated (\*) location at the impeller discharge exhibits a large number of nonlinear interaction components between the inflow forcing frequency  $f_F$  and the blade passing frequency  $f_{BP}$ . However, at these relatively high values of dimensionless forcing frequency  $f_F/f_{BP} = 0.78$  and  $0.88$ , the spectral peak at the inflow forcing frequency  $f_F$  is completely attenuated.

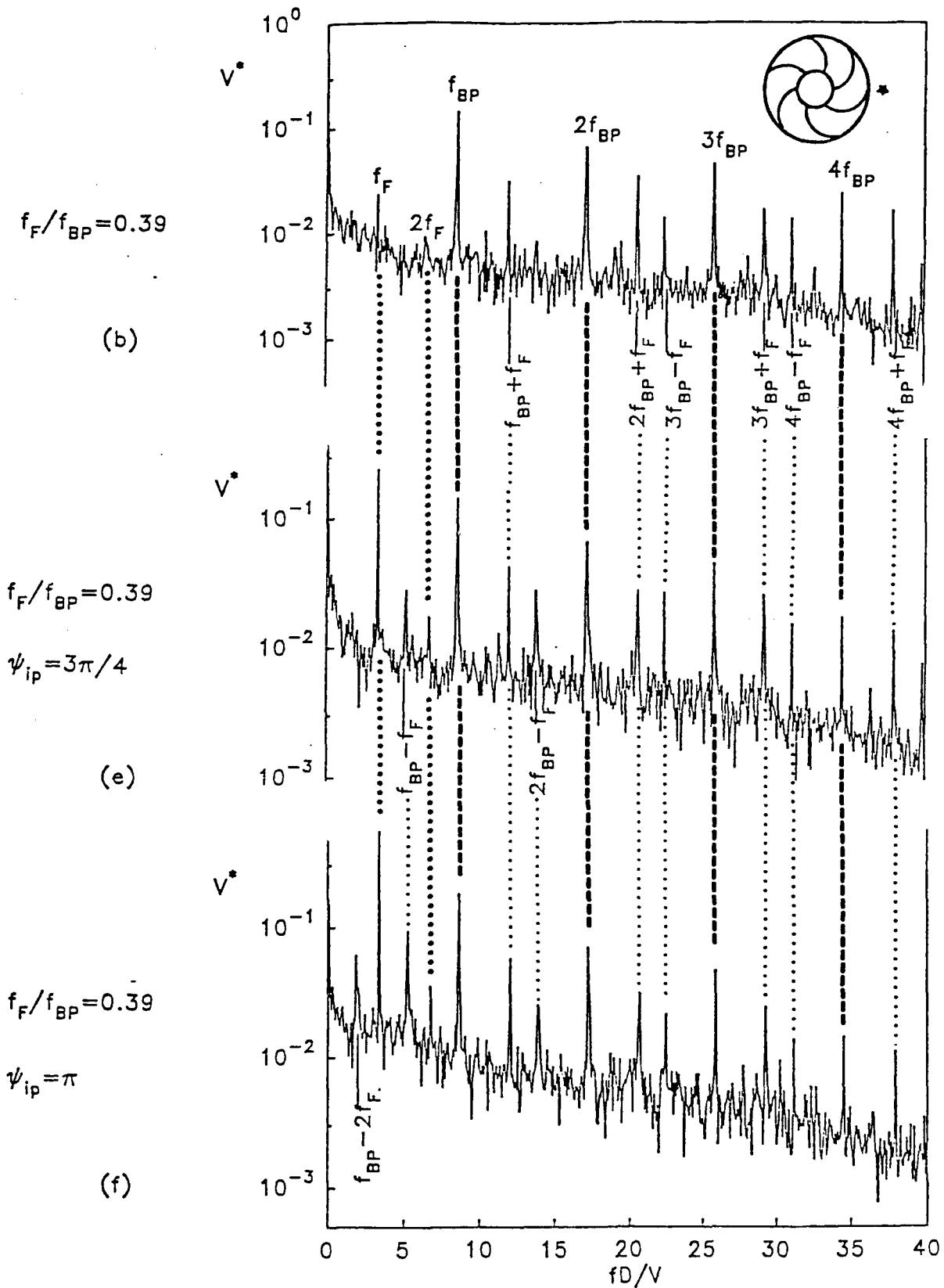


The power spectral density of the velocity fluctuation  $V^*$  is measured at the discharge of the impeller. The amplitude of the component at the inflow forcing frequency  $f_F$ , as well as the amplitude of higher order spectral components, is strongly dependent upon the amplitude of the tangential velocity fluctuation  $\bar{V}_i$  of the impeller relative to its mean tangential velocity  $\bar{V}_i$ . In the top plot, only the inflow is perturbed at a dimensionless frequency  $f_F/f_{BP} = 0.39$ . In the middle plot, the inflow is perturbed with the same condition, but accompanied by in-phase perturbations of the tangential velocity of the impeller at an amplitude of  $\bar{V}_i/\bar{V}_i = 0.1$ ; the amplitude of the component at forcing frequency  $f_F$  is nearly attenuated. In the bottom plot, the same excitation conditions hold as for the middle plot, except the dimensionless amplitude is increased to a value of  $\bar{V}_i/\bar{V}_i = 0.3$ ; the amplitude of the component  $f_F$  is actually amplified relative to that in the top plot. Consideration of a range of excitation conditions shows that the amplitude of the spectral component  $f_F$  is highly sensitive to the amplitude of the impeller perturbation  $\bar{V}_i/\bar{V}_i$ ; extremes of either complete attenuation or substantial amplification are attainable.

OVERALL RESPONSE TO CONTROLLED EXCITATION:  
ALTERATION OF FORCING COMPONENT

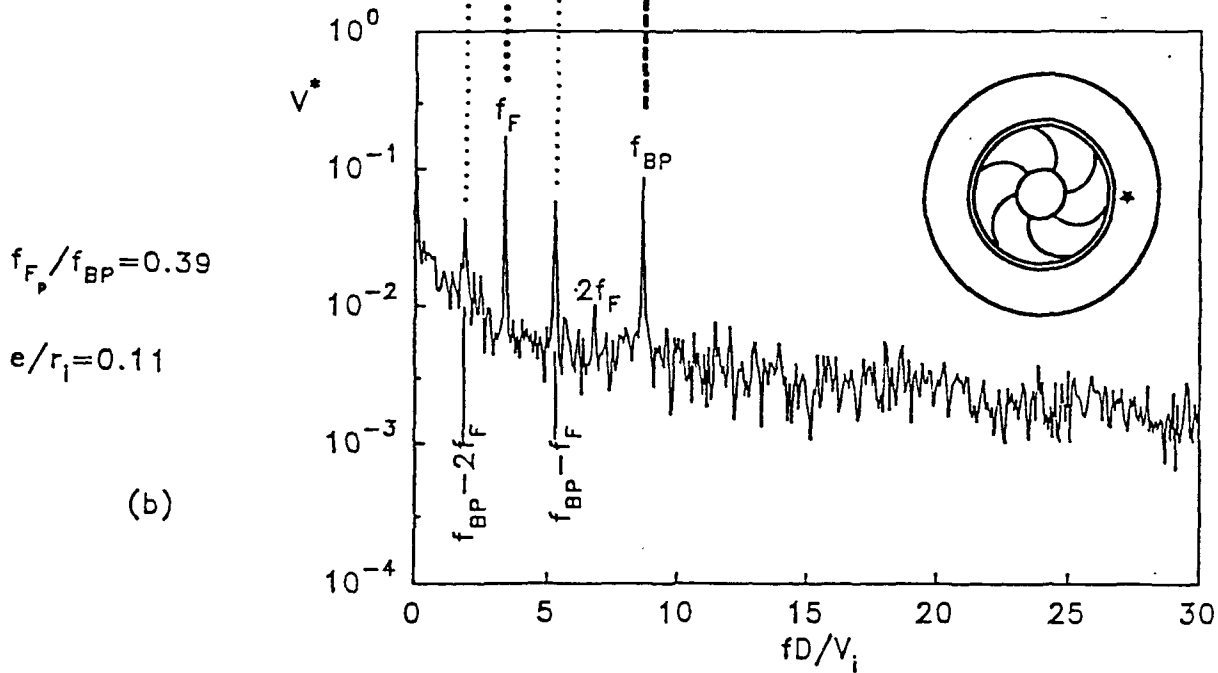
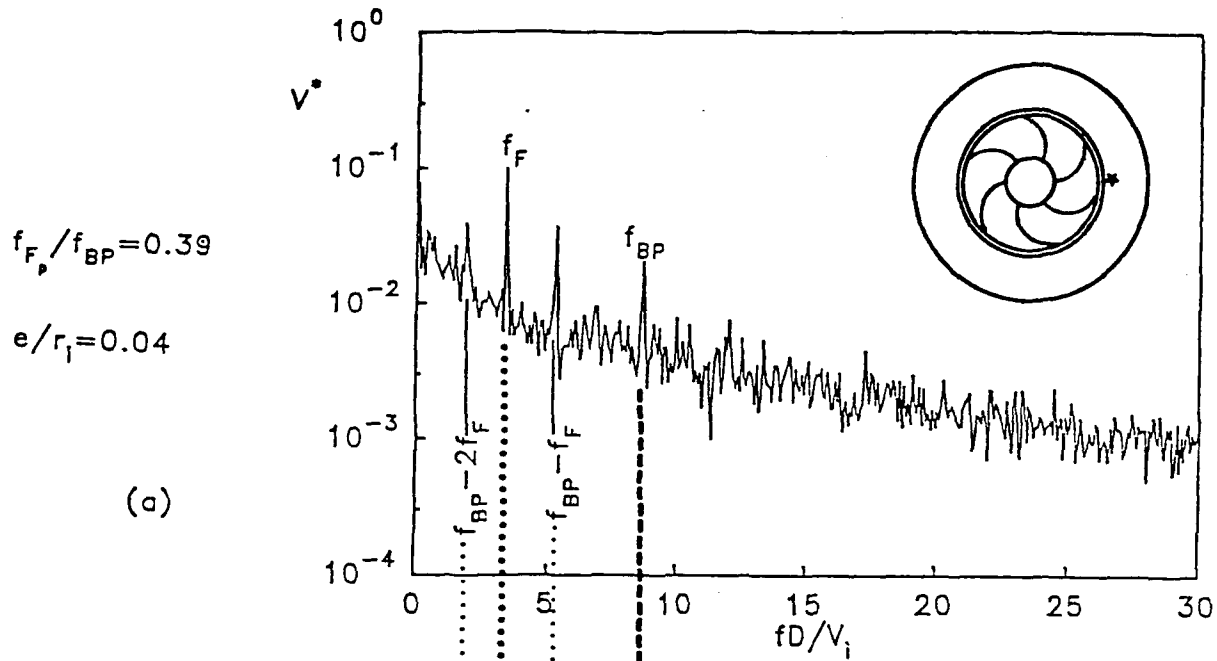


The power spectral density  $V^*$  of the velocity fluctuation is measured at the indicated (\*) location at the impeller discharge. Excitation of the inflow only at a dimensionless frequency  $f_F/f_{BP} = 0.39$ , where  $f_F$  is the forcing frequency and  $f_{BP}$  is the blade passing frequency, is represented by the top plot. In the middle and bottom plots, there is simultaneous excitation of the inflow velocity and the impeller tangential velocity, with the phase angle  $\psi_{ip}$  between them.



The power spectral density  $V^*$  of the velocity fluctuation is measured at the indicated (\*) location at the impeller discharge. Excitation of the inflow only at a dimensionless frequency  $f_F/f_{BP} = 0.39$  is shown in the top plot. In the middle and bottom plots, there is simultaneous excitation of the inflow velocity and the impeller tangential velocity, with the phase angle  $\psi_{ip}$  between them. The amplitudes of the spectral peaks in the lower frequency range are strongly influenced by the value of  $\psi_{ip}$ .

OVERALL RESPONSE TO CONTROLLED EXCITATION: DECAY OF  
DISCRETE SPECTRAL COMPONENTS IN VANELESS DIFFUSER



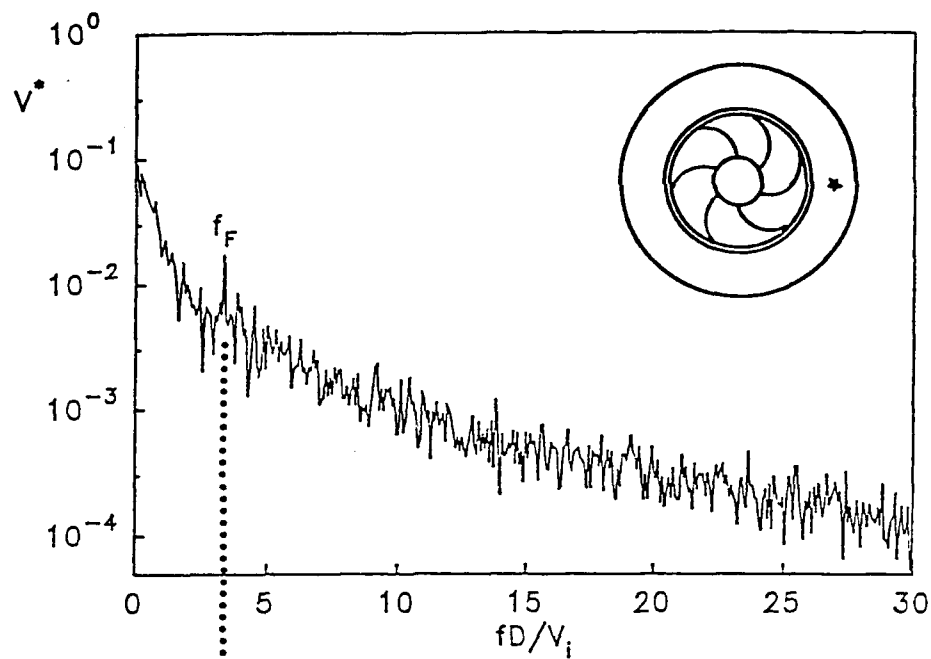
The power spectral density  $V^*$  of the velocity component is measured at the indicated (\*) location within the vaneless diffuser. Excitation of the inflow is at a dimensionless frequency  $f_F/f_{BP} = 0.39$ . As the distance  $e$ , relative to the radius  $r_i$  of the impeller, increases, the amplitudes of the discrete spectral components are altered. At large distances, the discrete spectral components are immersed in the broadband level.

OVERALL RESPONSE TO CONTROLLED EXCITATION: DECAY OF DISCRETE SPECTRAL COMPONENTS IN VANELESS DIFFUSER

$f_{F_p}/f_{BP}=0.39$

$e/r_i=0.19$

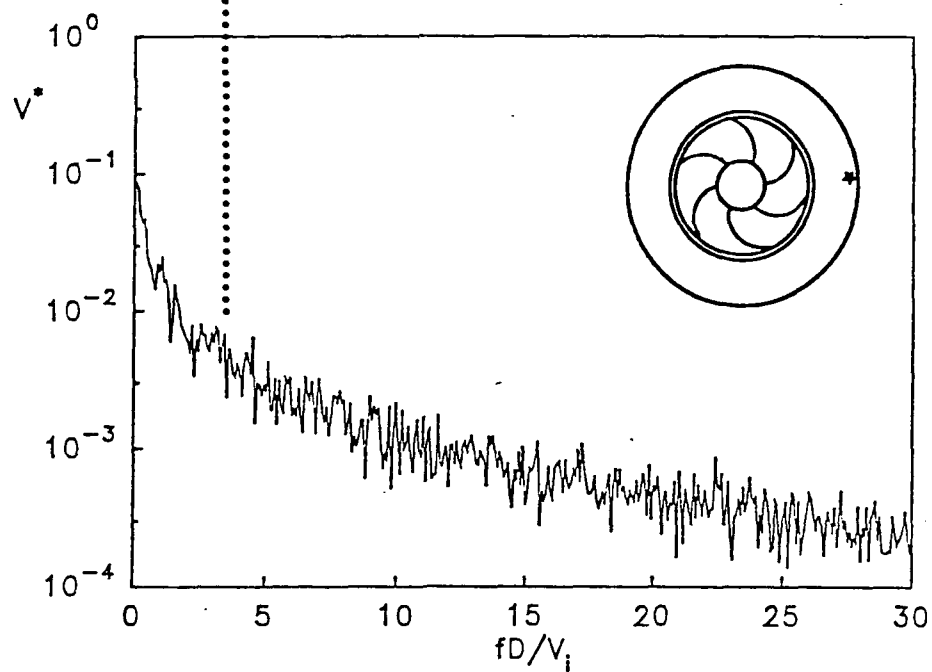
(c)

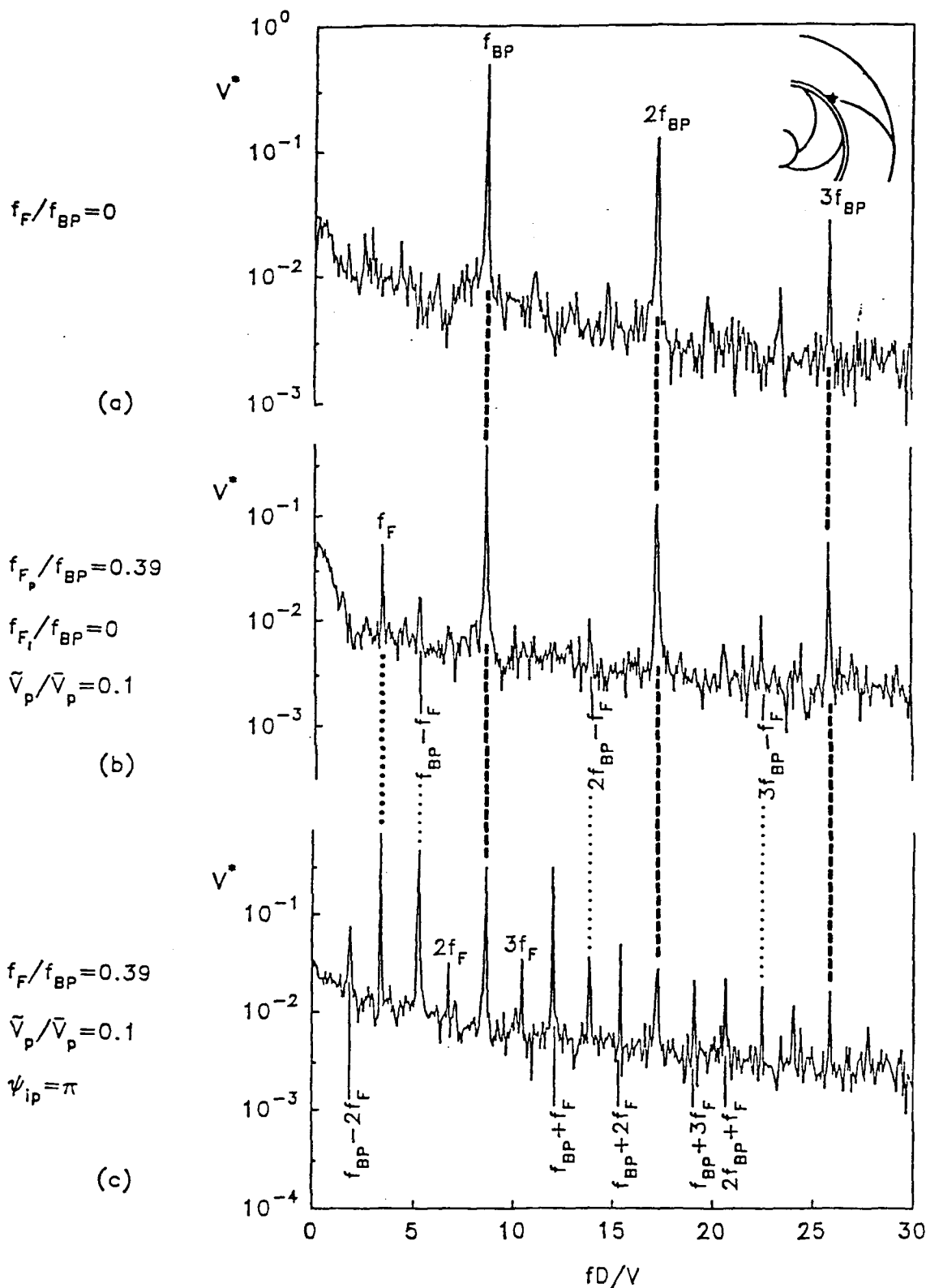


$f_{F_p}/f_{BP}=0.39$

$e/r_i=0.44$

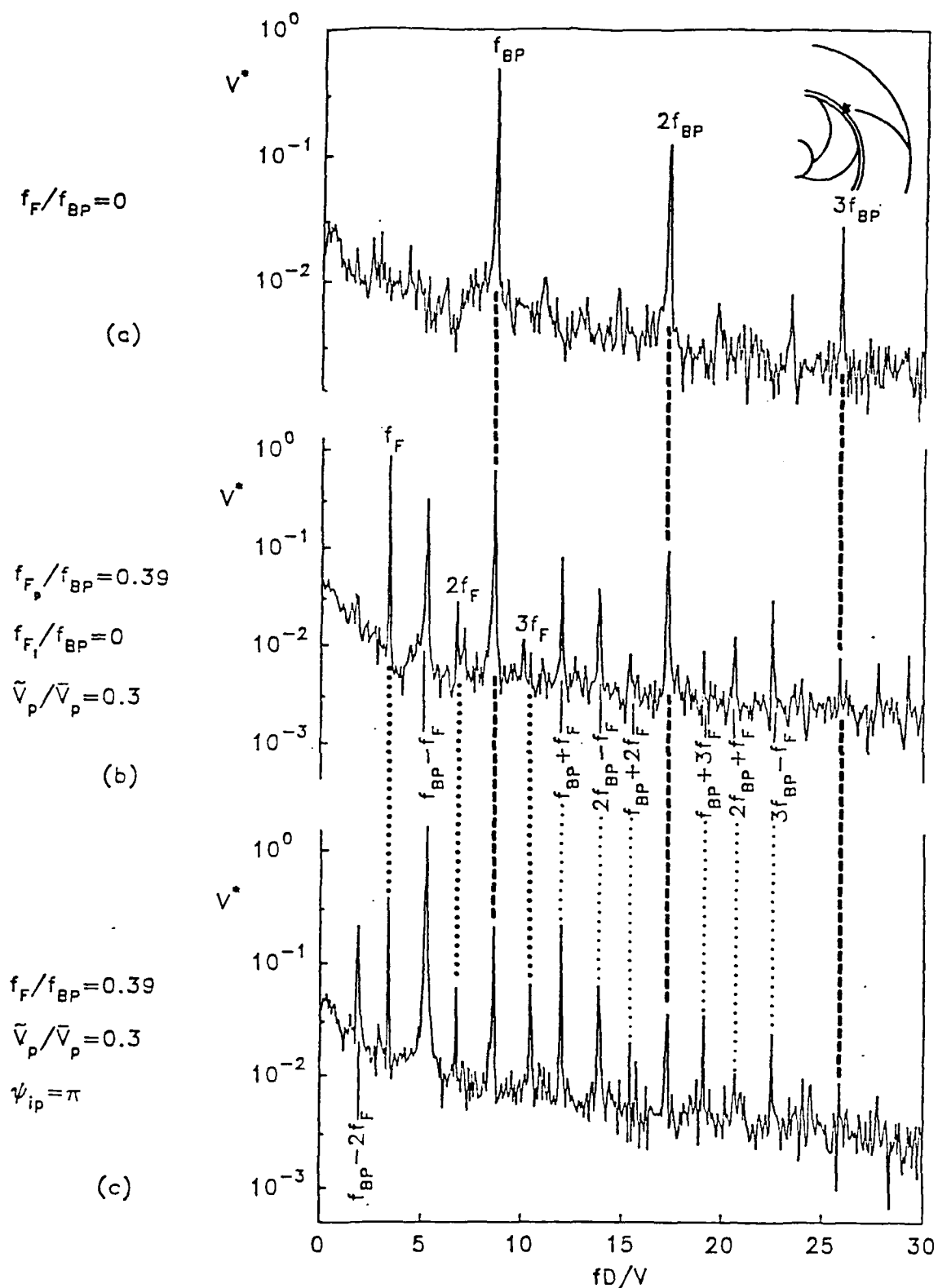
(d)





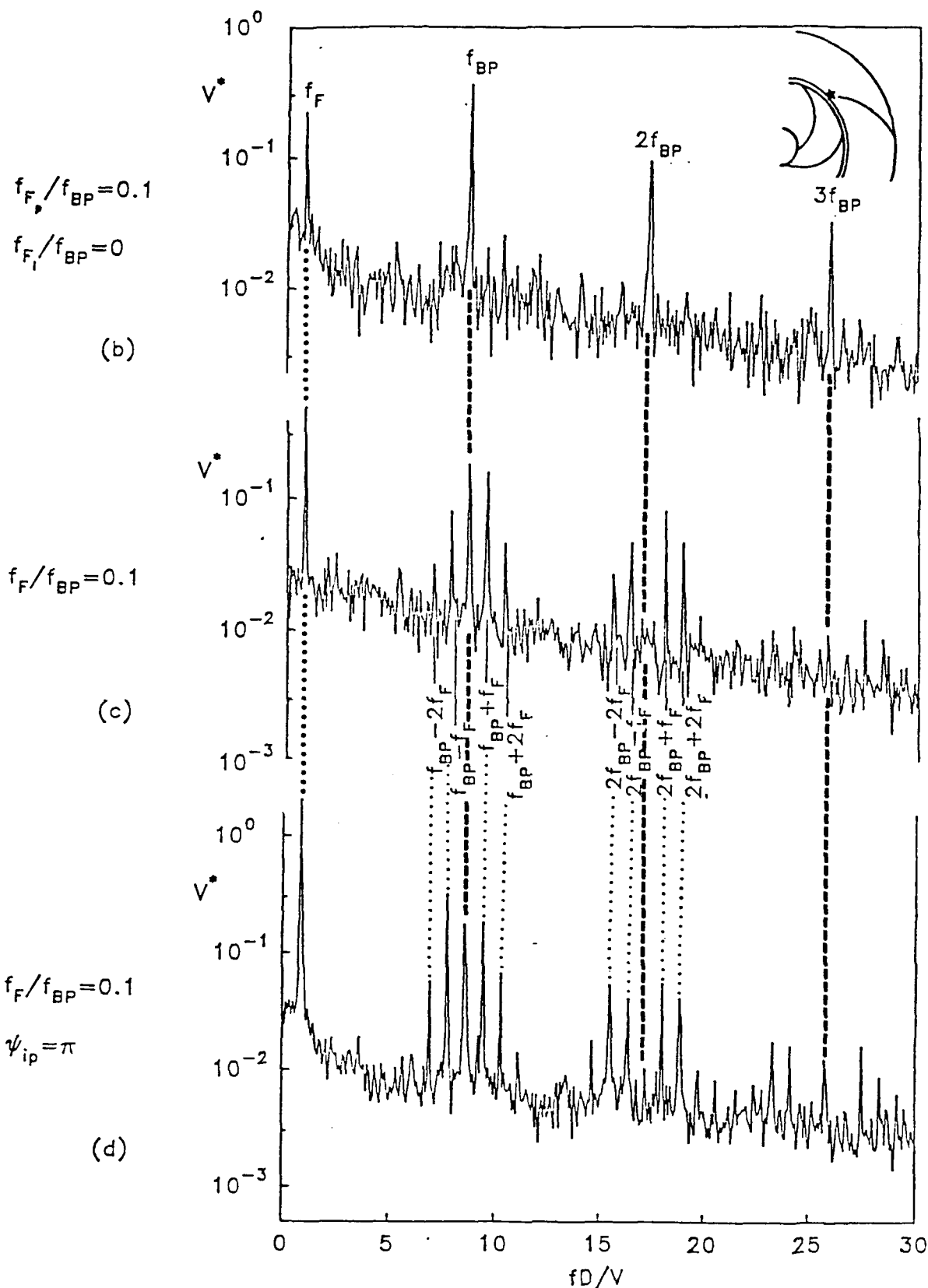
The amplitude of the power spectral density  $V^*$  of the velocity fluctuation is measured at indicated (\*) location between discharge of impeller and leading-edge of stationary diffuser blade. In the top plot, no external forcing is imposed. In the middle plot, there is forcing only of the inlet flow at an excitation frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$ , i.e.  $f_F/f_{BP} = 0.39$  and at an amplitude of the inflow velocity  $\bar{V}_p$  relative to the mean inflow velocity of  $\bar{V}_p/\bar{V}_p = 0.1$ . Finally, in the bottom plot, the same excitation conditions were applied for the inflow, but in presence of a perturbation of the tangential velocity of the impeller at a phase angle  $\psi_{ip} = \pi$  relative to the inflow perturbation. Very substantial manipulation of the discrete spectral components is attainable, especially in the presence of simultaneous inflow and impeller perturbations.



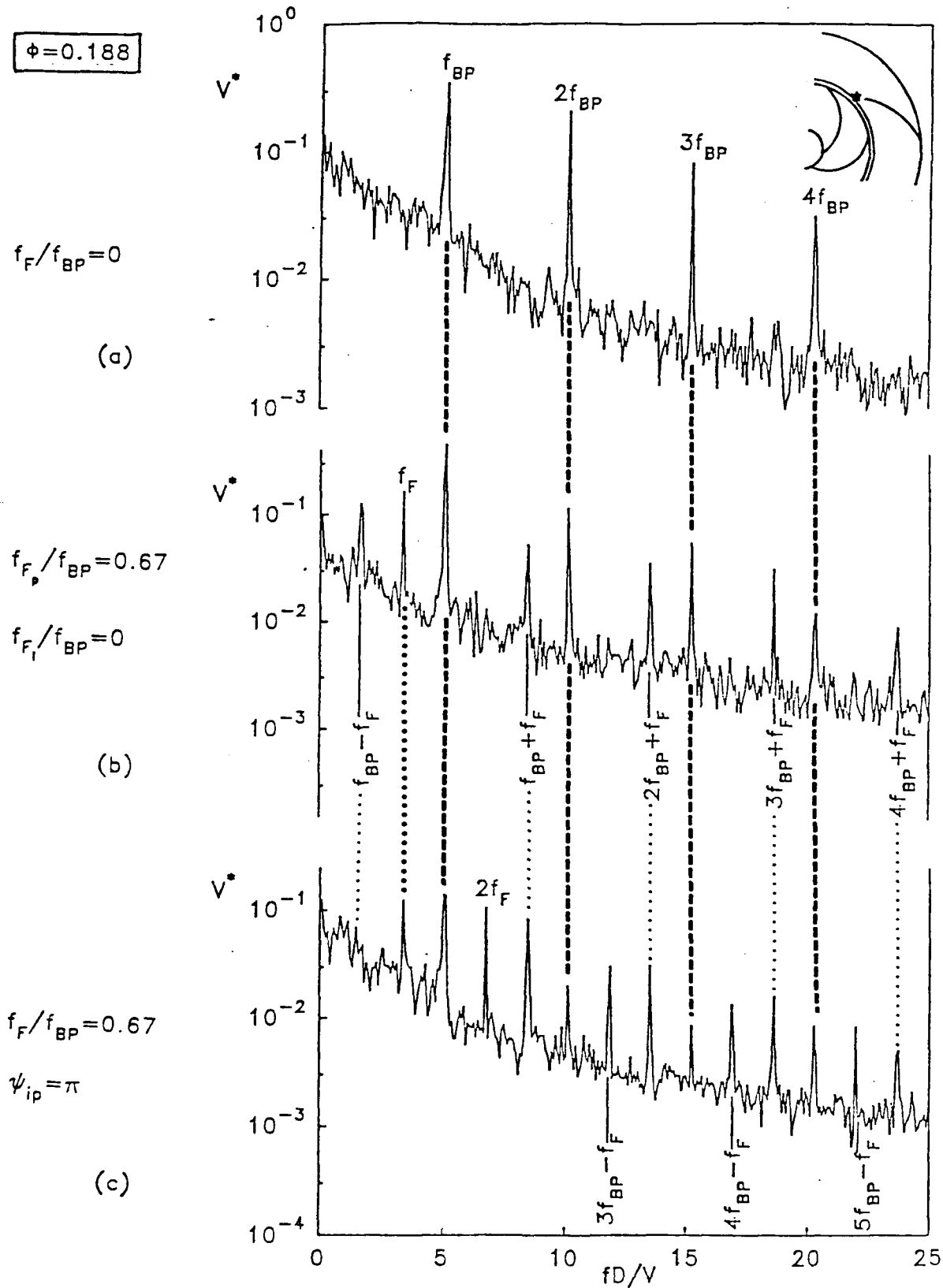


The amplitude of the power spectral density  $V^*$  of velocity fluctuation is measured at the indicated (\*) location between the discharge of the impeller and the leading-edge of the stationary diffuser blade. In the top plot, no external forcing is imposed. In the middle plot, there is forcing only of the inlet flow at an excitation frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$ , i.e.  $f_F/f_{BP} = 0.39$  and at an amplitude of the inflow velocity  $\tilde{V}_p$  relative to the mean inflow velocity of  $\bar{V}_p$ ,  $\tilde{V}_p/\bar{V}_p = 0.3$ . Finally, in the bottom plot, the same excitation conditions were applied for the inflow, but in presence of a perturbation of the tangential velocity of the impeller at a phase angle  $\psi_{ip} = \pi$  relative to the inflow perturbation. Very substantial manipulation of the discrete spectral components is attainable, especially in the presence of simultaneous inflow and impeller perturbations.

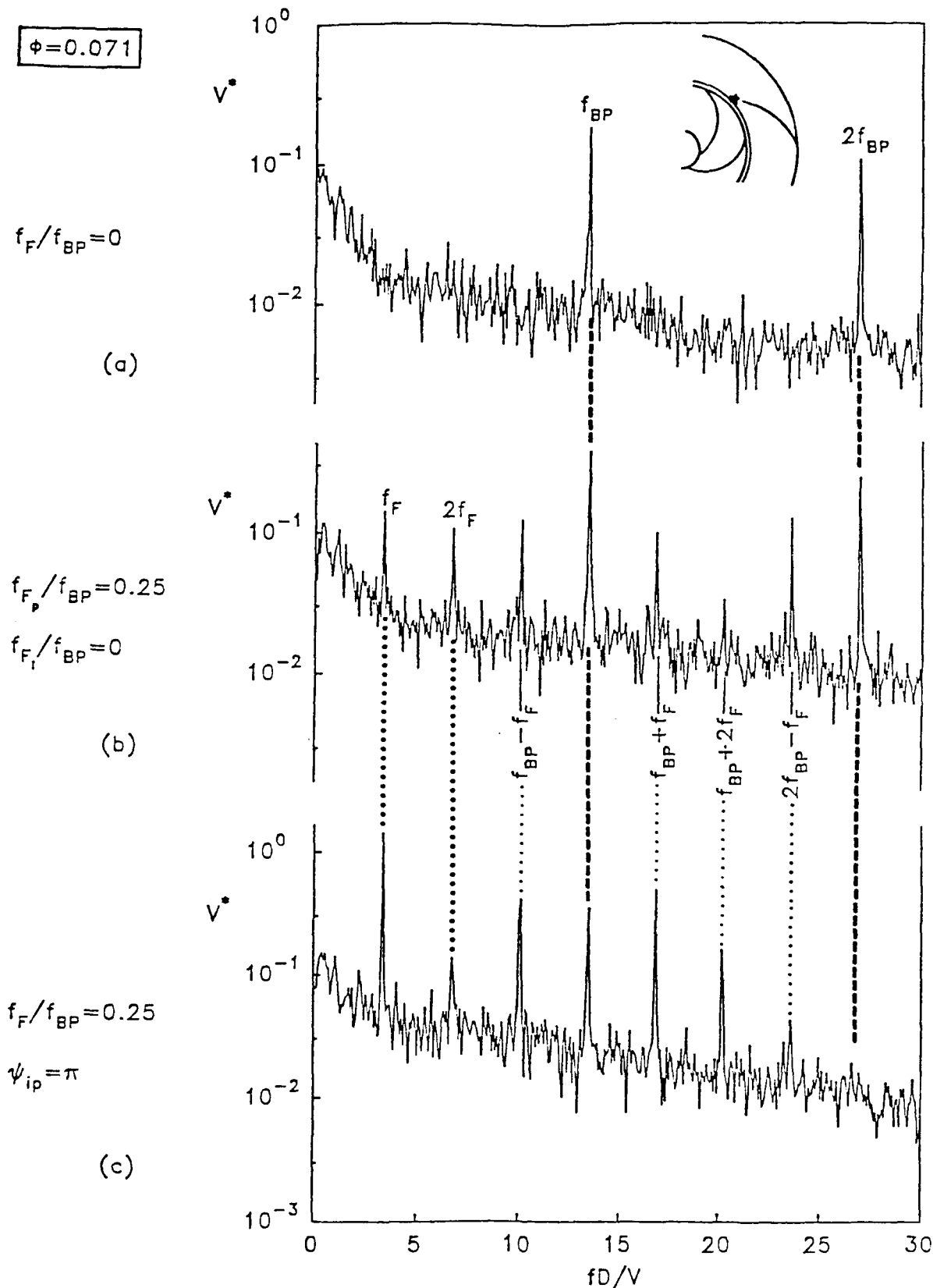
EFFECTS OF CONTROLLED EXCITATION IN PRESENCE OF DIFFUSER  
BLADE: EFFECTS OF INFLOW AND IMPELLER PERTURBATIONS



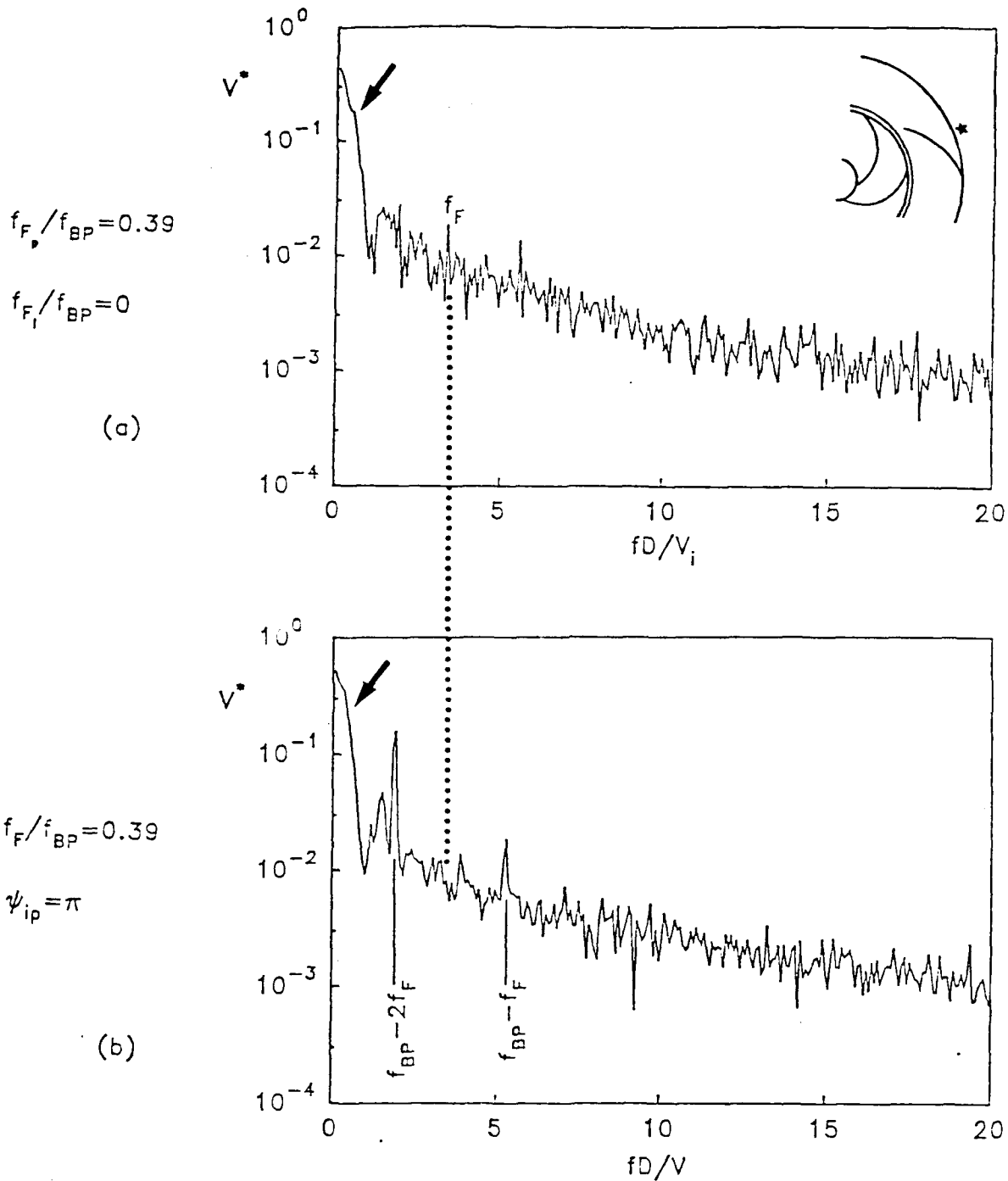
The power spectral density  $V^*$  of the velocity fluctuation is measured in the gap between the discharge of the impeller and the leading-edge of the diffuser blade. In the top plot, only the inflow is perturbed at a relatively low forcing frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$ , i.e.  $f_F/f_{BP} = 0.1$ . In the middle plot, both the inflow and impeller are perturbed with zero phase angle between them, and in the bottom plot both the inflow and impeller are perturbed with a phase shift  $\psi_{ip} = \pi$  between them. These results show that at this relatively low value of excitation frequency  $f_F/f_{BP} = 0.1$ , it is necessary to perturb both the inflow and impeller in order to generate a large number of nonlinear interaction components.



The power spectral density  $V^*$  of the velocity fluctuation is measured at the indicated (\*) location between the discharge of the impeller and the leading-edge of the diffuser blade for an off-design flow coefficient  $\Phi = 0.188$ . In the top plot, no perturbations are applied. In the middle plot, there is excitation only of the inflow at frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$  of  $f_F/f_{BP} = 0.67$ . In the bottom plot, there is simultaneous excitation of the inflow velocity and the tangential velocity of the impeller at a dimensionless frequency  $f_F/f_{BP} = 0.67$ , and with the phase angle between the perturbations of the  $\psi_{ip} = \pi$ .



The power spectral density  $V^*$  of the velocity fluctuation is measured at the indicated (\*) location between the discharge of the impeller and the leading-edge of the diffuser blade for an off-design flow coefficient  $\Phi = 0.071$ . In the top plot, no perturbations are applied. In the middle plot, there is excitation only of the inflow at frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$  of  $f_F/f_{BP} = 0.25$ . In the bottom plot, there is simultaneous excitation of the inflow velocity and tangential velocity of the impeller at a dimensionless frequency  $f_F/f_{BP} = 0.67$ , with a phase angle between the perturbations of  $\psi_{ip} = \pi$ .



The power spectral density  $V^*$  of velocity fluctuation is measured at the exit of the diffuser in presence of a stationary diffuser blade. In the top plot, perturbations of the inflow at frequency  $f_F$  relative to the blade passing frequency  $f_{BP}$  of  $f_F/f_{BP} = 0.39$  are applied. In the bottom plot, the same excitation condition holds for both the inflow and tangential velocity of the impeller, with the phase angle  $\psi_{ip} = \pi$  between them. Note the large amplitude of the low frequency fluctuations generated in both cases. Different discrete components are evident at this location, depending upon the condition of excitation with or without perturbation of the impeller.

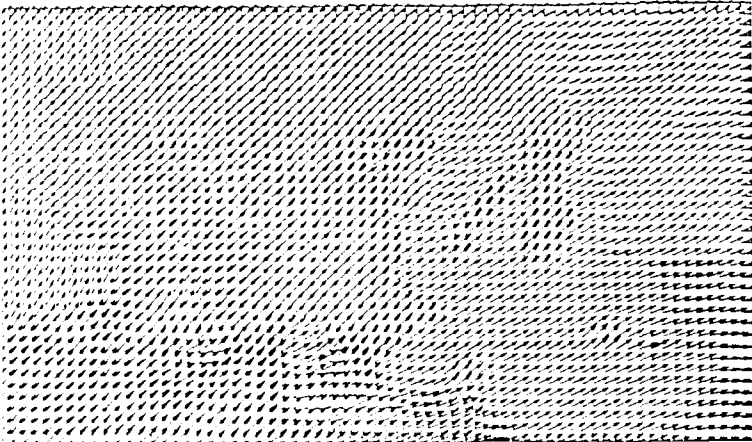
## OVERALL RESPONSE TO CONTROLLED EXCITATION: SUMMARY

- I. POSSIBLE TYPES OF RESPONSE DUE TO OSCILLATIONS OF INFLOW AT FREQUENCY  $f_F$ 
  - GENERATION OF LARGE NUMBER OF DISCRETE COMPONENTS AT  $nf_F \pm mf_{BP}$
  - ATTENUATION OF DISCRETE COMPONENTS AT  $f_F$  AND  $f_{BP}$
  - ALTERATION OF LOW FREQUENCY, BROADBAND CONTRIBUTIONS
  
- II. POSSIBLE TYPES OF RESPONSE DUE TO SIMULTANEOUS OSCILLATIONS OF INFLOW AND IMPELLER AT FREQUENCY  $f_F$ 
  - GENERATION OF LARGE NUMBER OF DISCRETE COMPONENTS AT  $nf_F \pm mf_{BP}$  EVEN AT LOW  $f_F$
  - ENHANCEMENT OR ATTENUATION OF COMPONENT  $f_F$ ; ATTENUATION OF COMPONENT AT  $f_{BP}$
  
- III. POSSIBLE IMPLICATIONS OF FOREGOING DISCRETE RESPONSE FOR LOW FREQUENCY, BROADBAND RESPONSE
  - LOCAL ALTERATIONS OF LOW FREQUENCY BROADBAND RESPONSE
  - INITIAL CONDITIONS FOR SPATIAL DELAY OF DISCRETE COMPONENTS TO BROADBAND FLUCTUATIONS IN VANELESS DIFFUSER
  - INITIAL CONDITIONS FOR LOW FREQUENCY STALL FLUCTUATIONS ALONG DIFFUSER BLADE

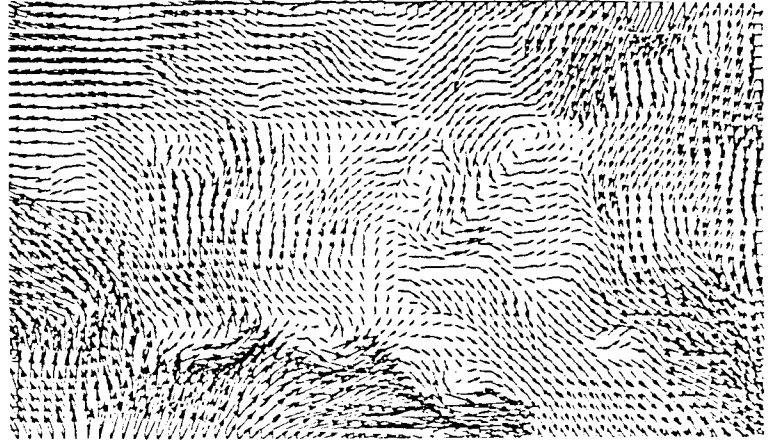
## UNSTEADY FLOW DISTORTION PAST BLADES

- OBJECTIVES
- RESEARCH PLAN
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS
- EXPERIMENTAL TECHNIQUES
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION
  - ✓ LEADING-EDGE
  - ✓ TRAILING-EDGE
  - ✓ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS
  - ✓ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - ✓ ACTIVELY-CONTROLLED PUMPING SYSTEM
- FLOW STRUCTURE IN ACTIVELY-CONTROLLED RADIAL-FLOW MACHINE
  - ✓ OVERALL SYSTEM RESPONSE
  - ⊙ ✓ FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER
  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES ALONG DIFFUSER BLADE OR CUTOFF
  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
  - ✓ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

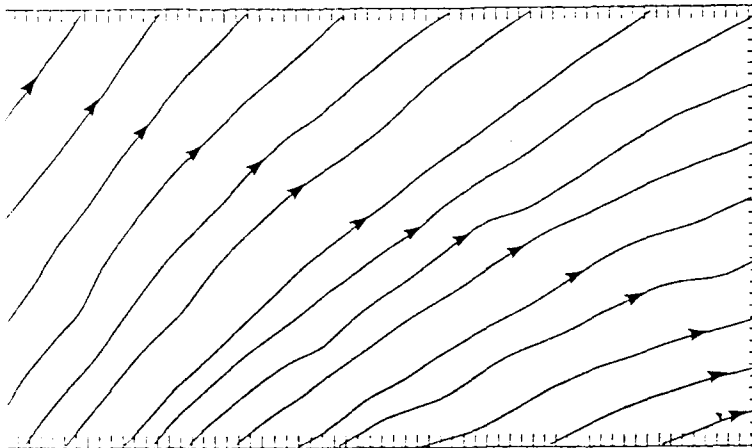
# FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER



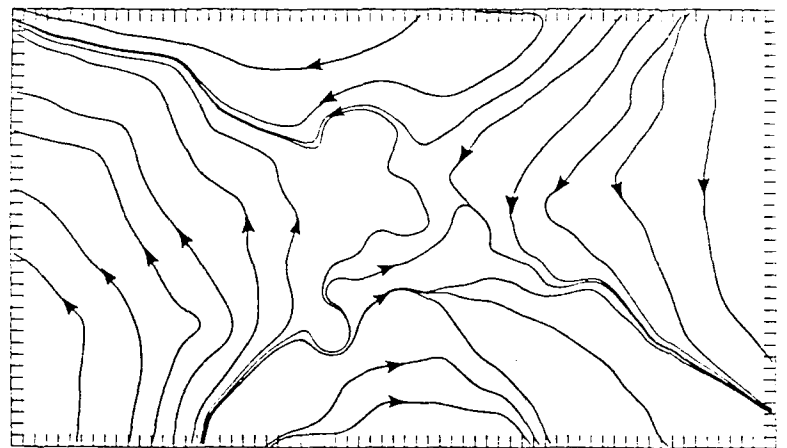
VELOCITY FIELD IN LABORATORY  
REFERENCE FRAME



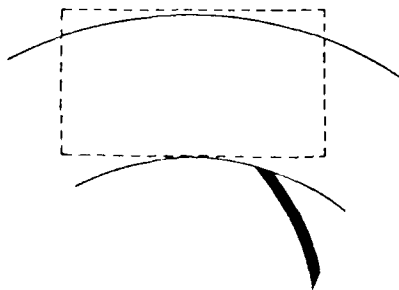
VELOCITY FIELD IN  
BIASED FRAME



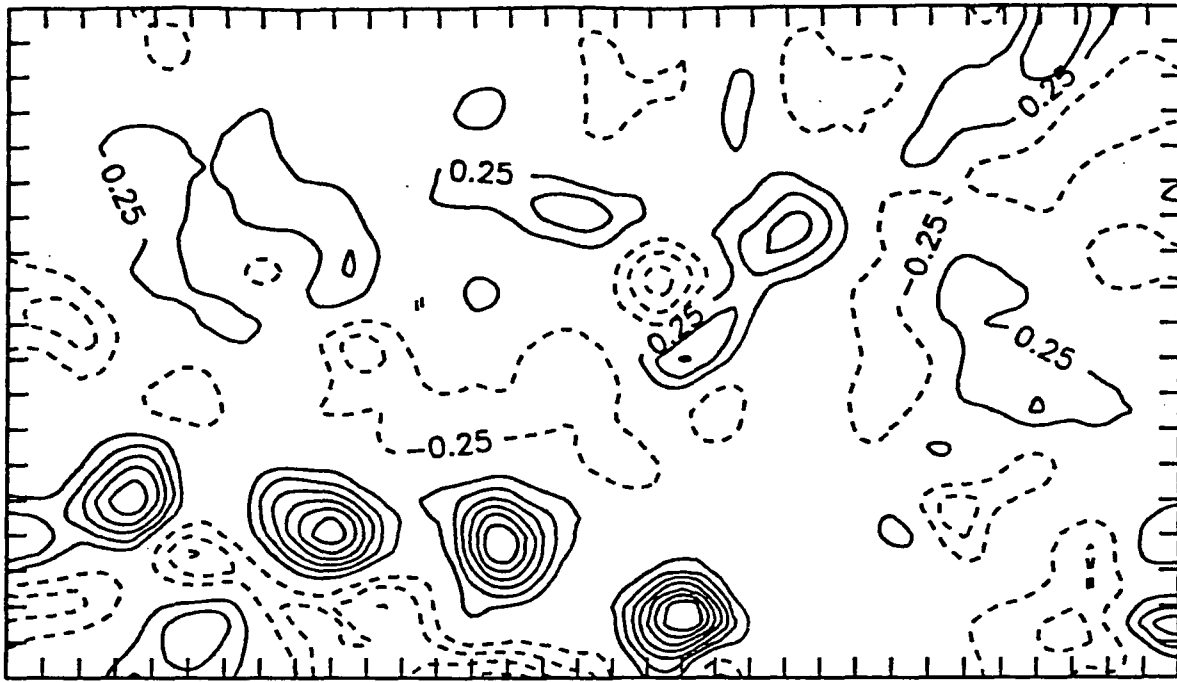
STREAMLINE PATTERN IN  
LABORATORY FRAME



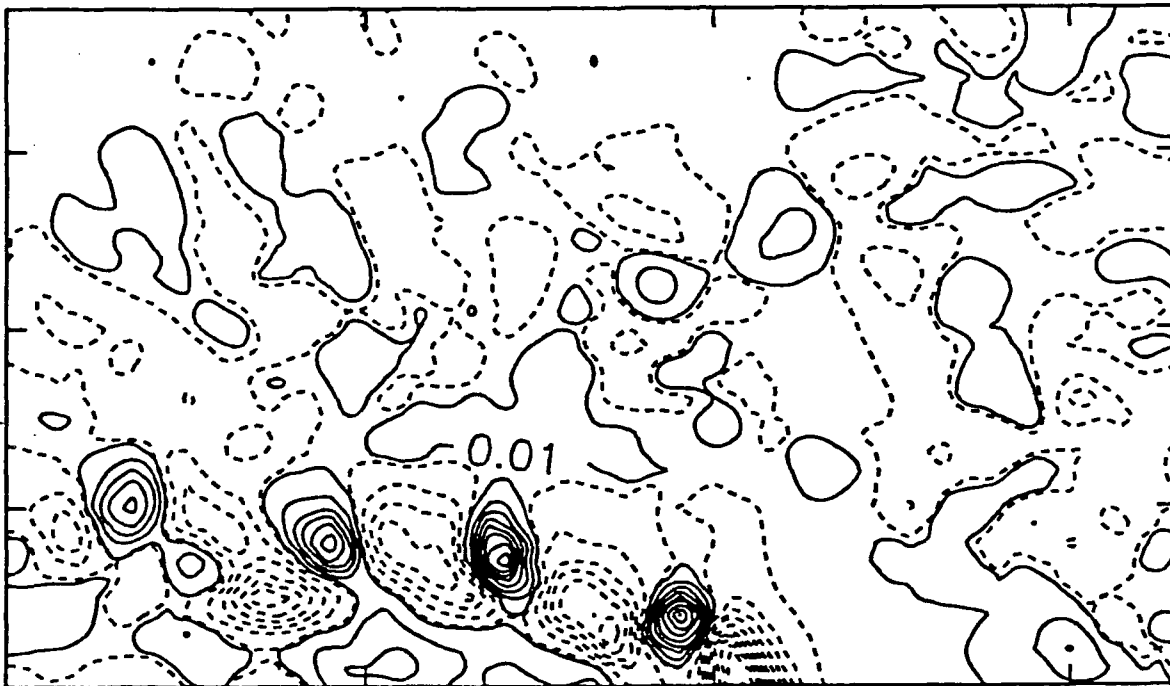
STREAMLINE PATTERN  
IN BIASED FRAME



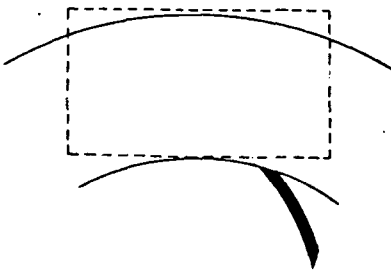




INSTANTANEOUS VORTICITY  $(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y})$



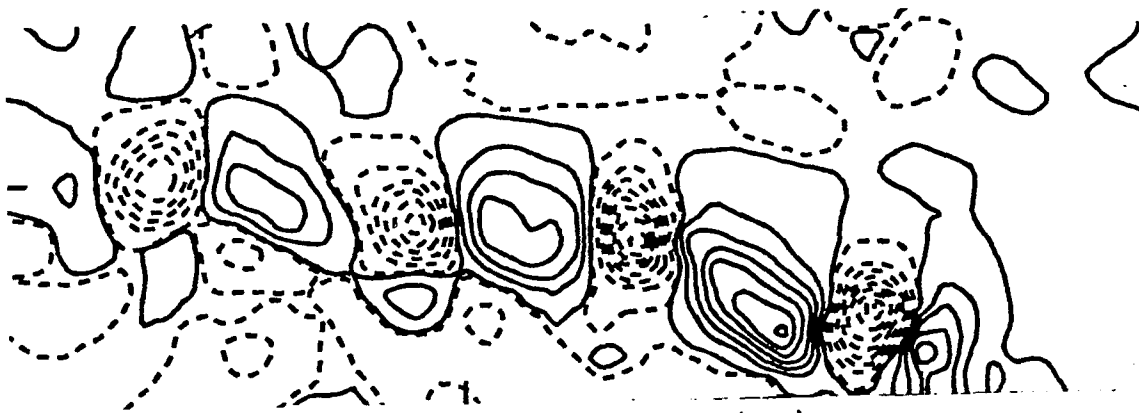
INSTANTANEOUS PRESSURE SOURCE TERM  $(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x})$



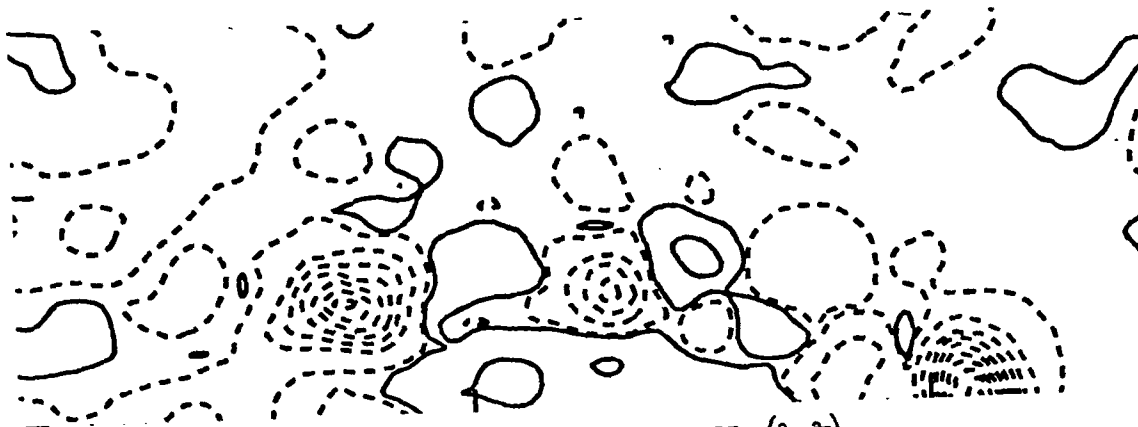
# FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER



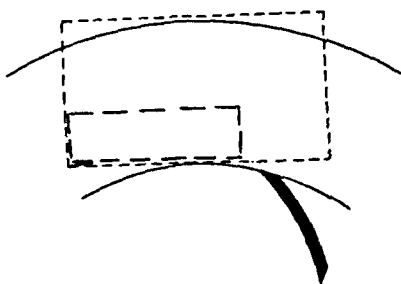
TOTAL INSTANTANEOUS SOURCE  $\left(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x}\right)$

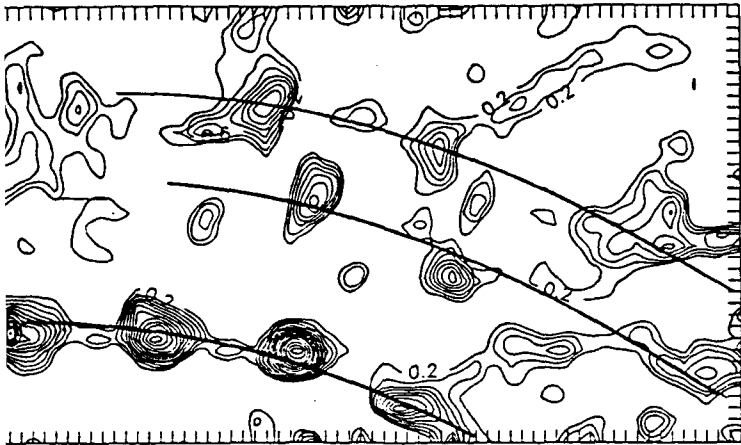


VORTICITY-RELATED SOURCE  $\left(\frac{\partial u}{\partial y} \frac{\partial v}{\partial x}\right)$



RATE-OF-STRAIN-RELATED SOURCE  $\left(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y}\right)$

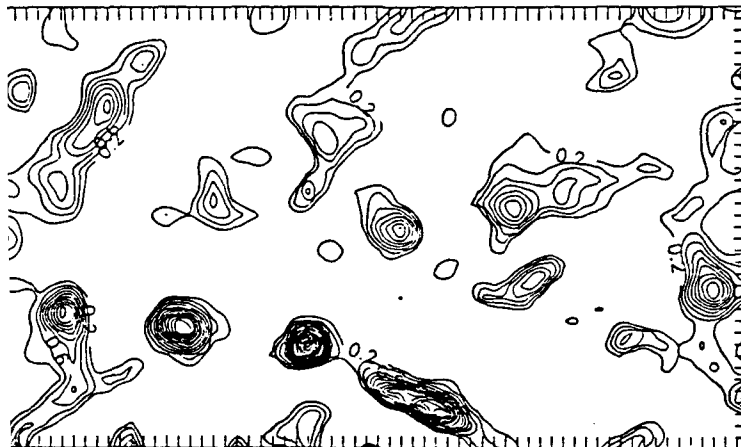




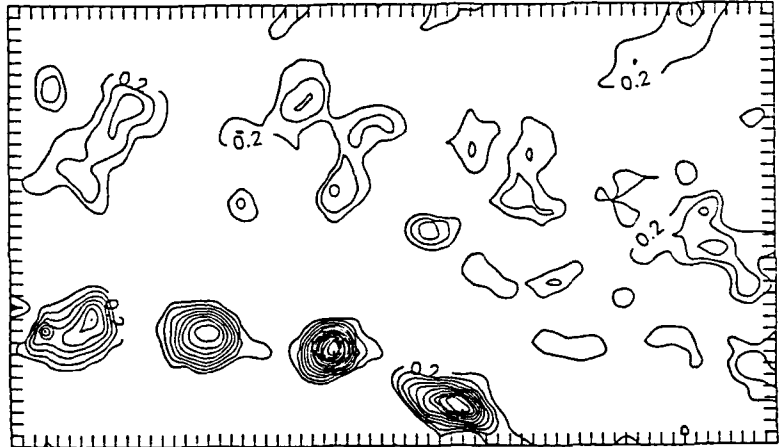
INSTANTANEOUS (POSITIVE) VORTICITY:  
REALIZATION #1



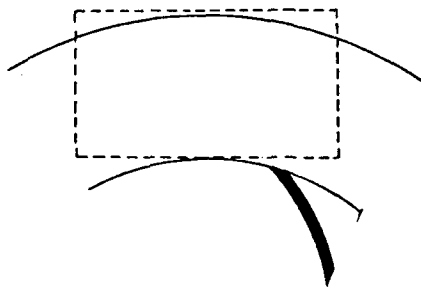
INSTANTANEOUS (POSITIVE) VORTICITY:  
REALIZATION #2



INSTANTANEOUS (POSITIVE) VORTICITY:  
REALIZATION #3



AVERAGE OF THREE REALIZATIONS OF  
INSTANTANEOUS (POSITIVE) VORTICITY

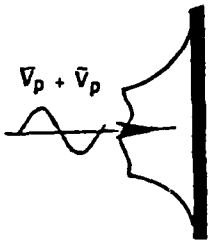


## UNSTEADY FLOW DISTORTION PAST BLADES

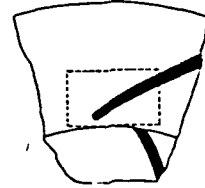
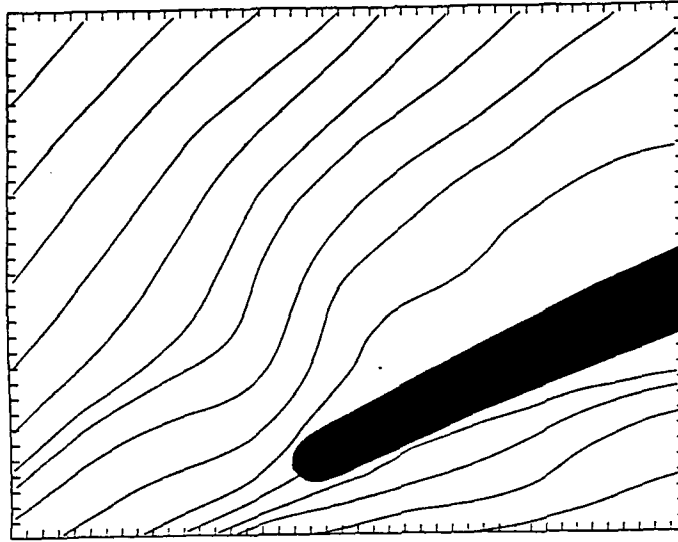
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  - ✓ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

# FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

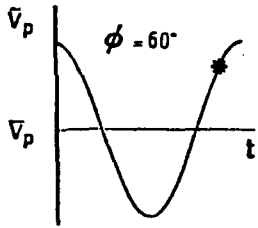
## STREAMLINES IN LABORATORY REFERENCE FRAME



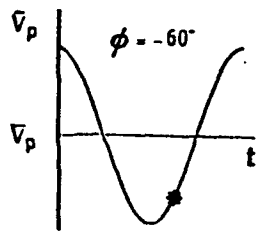
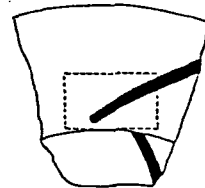
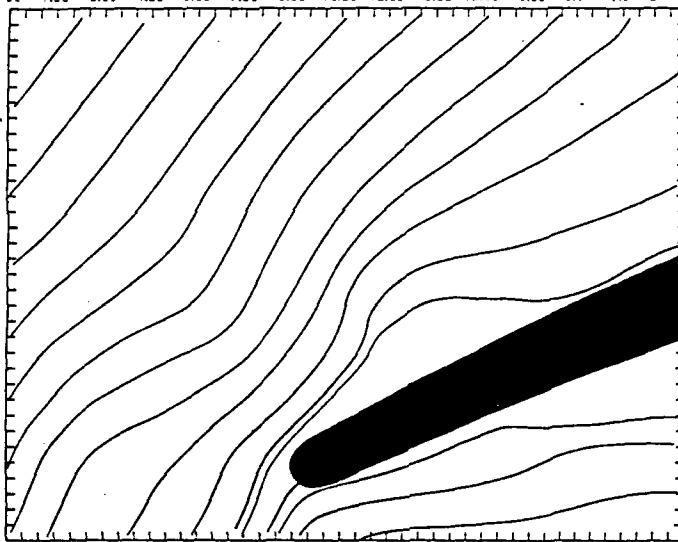
$f_p/f_{bp} = 0$



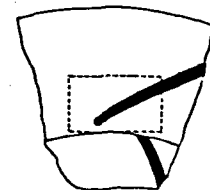
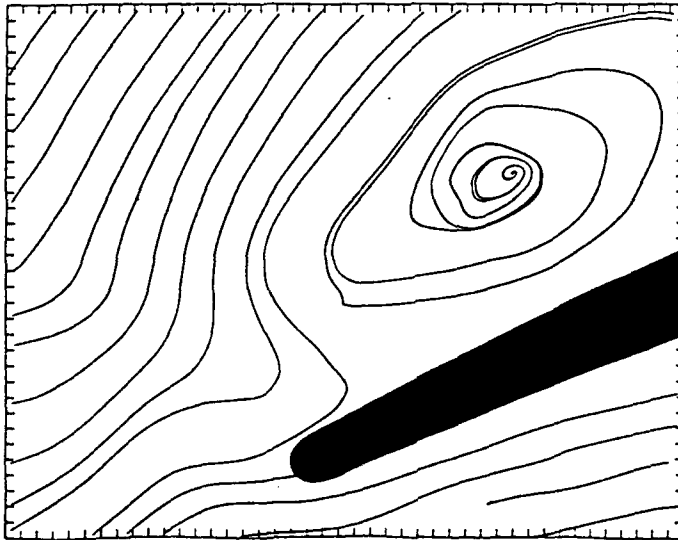
FLOW COEFFICIENT  
 $\phi = 0.188$



$f_p/f_{bp} = 0.67$



$f_p/f_{bp} = 0.67$

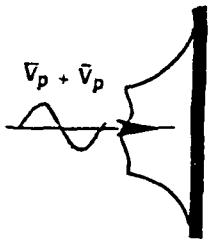


# FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

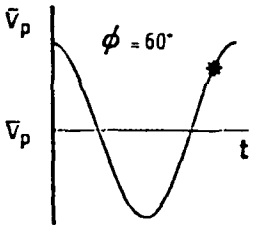
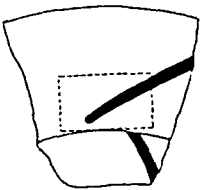
VORTICITY  $\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$

IB = VORTICITY FROM  
IMPELLER BLADE

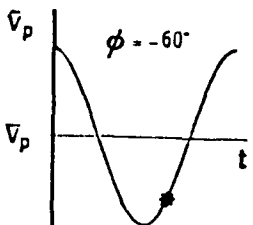
DB = VORTICITY FROM  
DIFFUSER BLADE



$f_p/f_{bp} = 0$

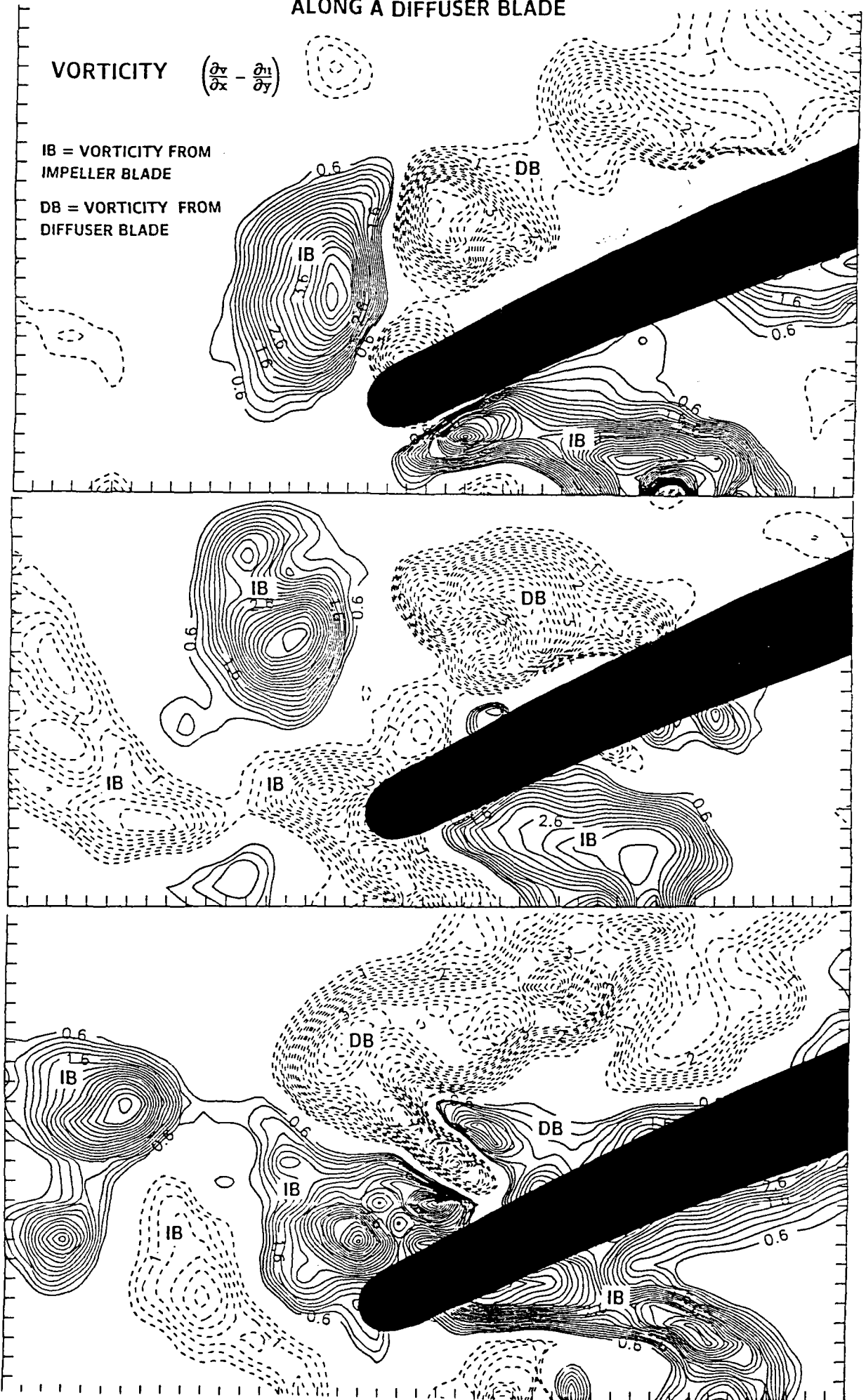


$f_p/f_{bp} = 0.67$



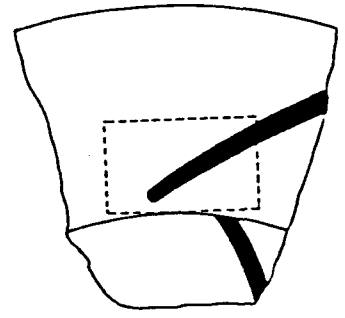
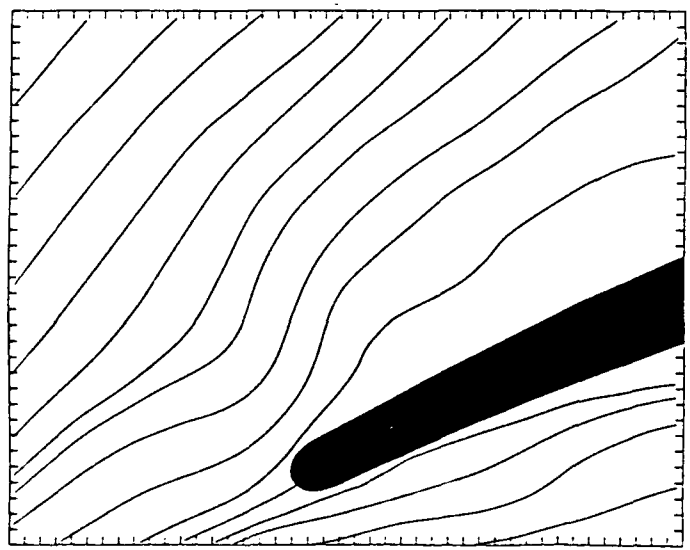
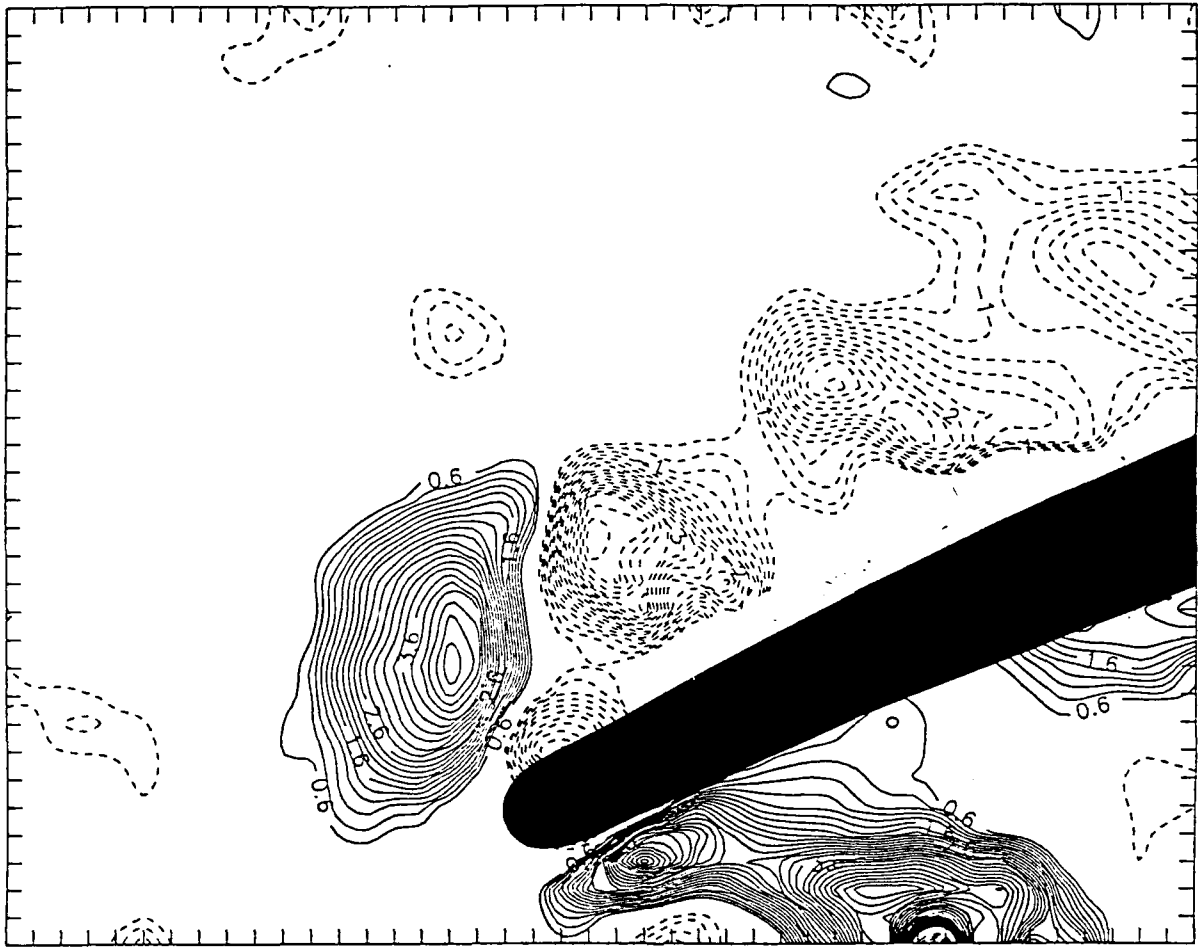
$f_p/f_{bp} = 0.67$

FLOW COEFFICIENT  
 $\phi = 0.183$



# FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

## VORTICITY

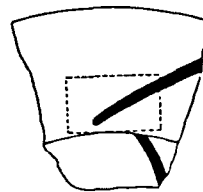
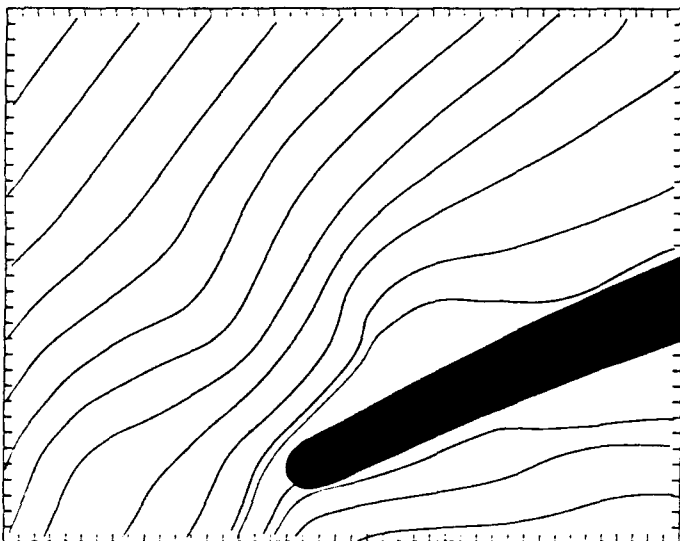
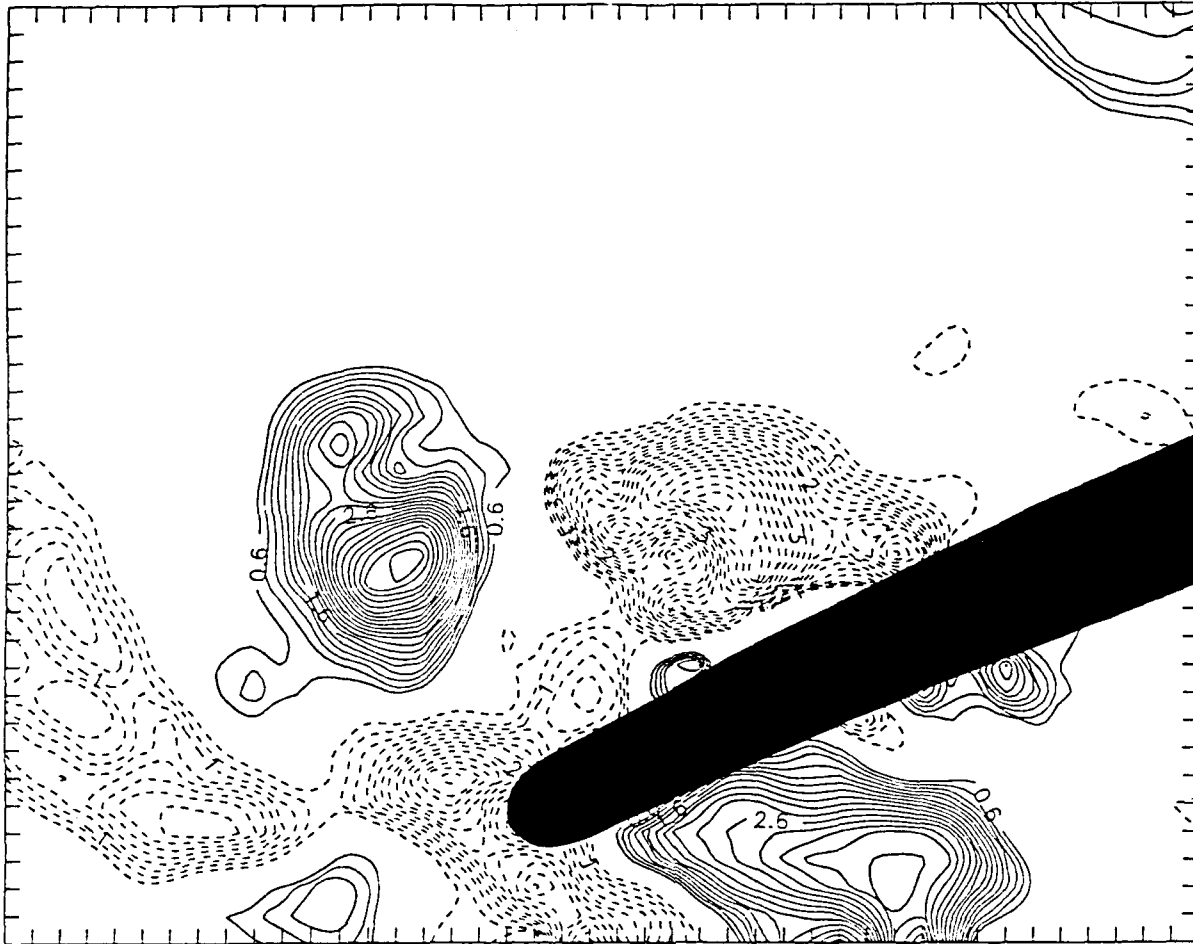


$$f_p / r_{bp} = 0$$

FLOW COEFFICIENT  
 $\phi = 0.183$

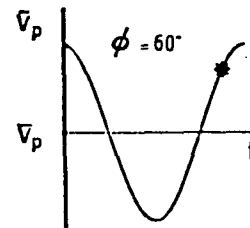
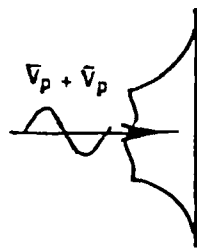
# FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE

## VORTICITY



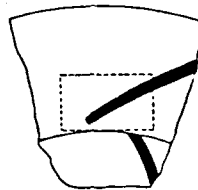
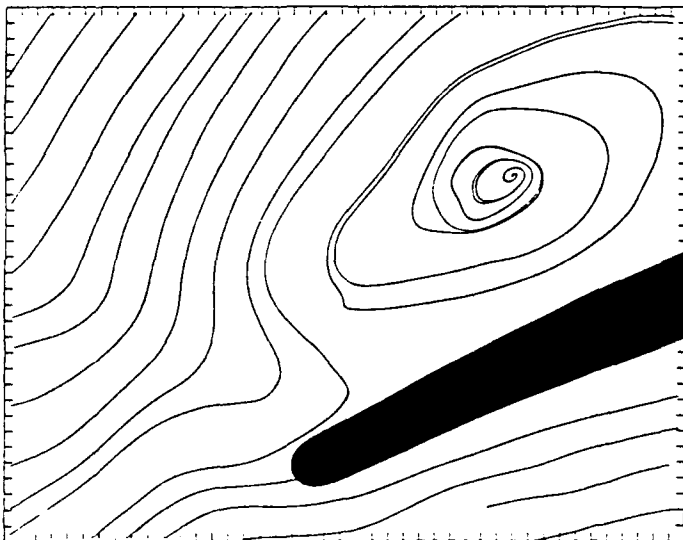
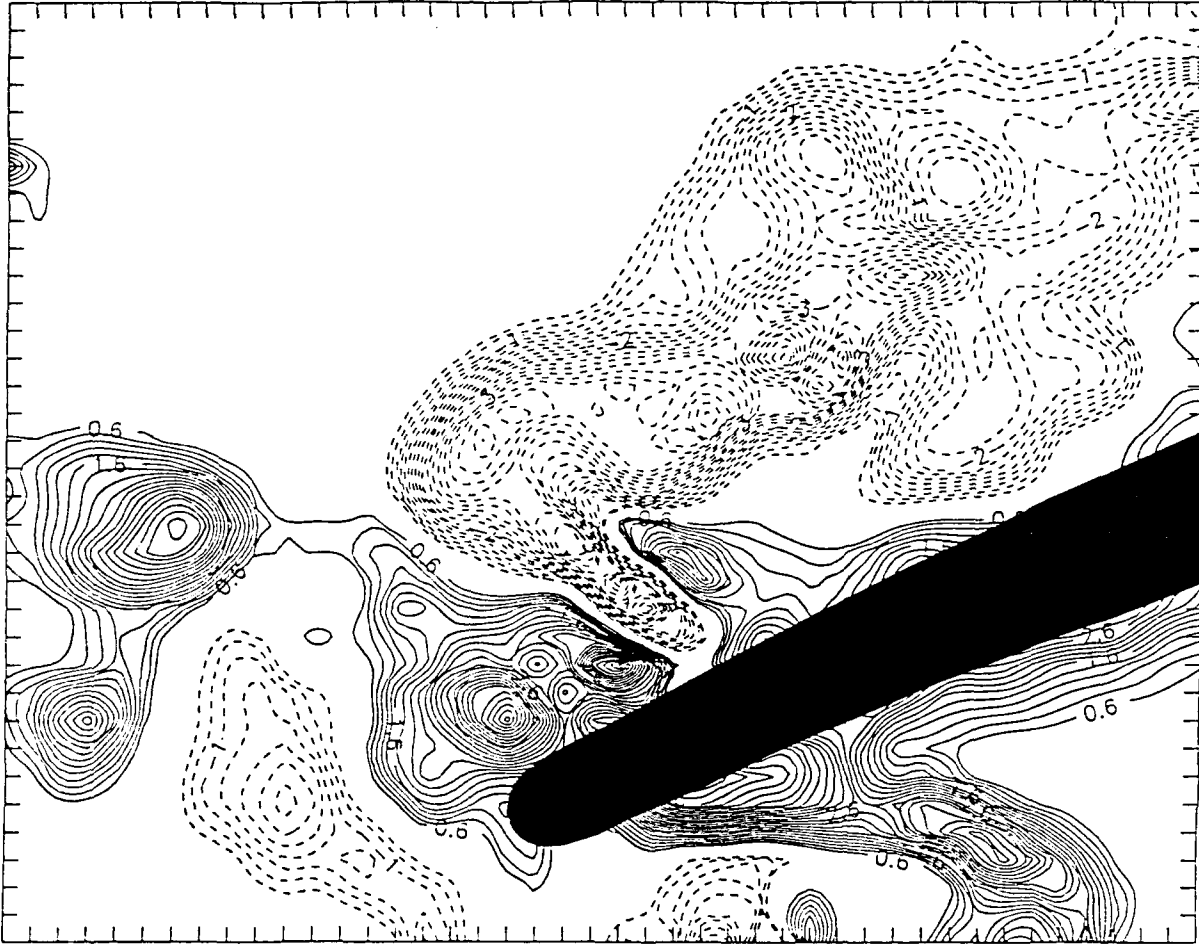
$f_p/f_{bp} = 0.67$

FLOW COEFFICIENT  
 $\phi = 0.188$



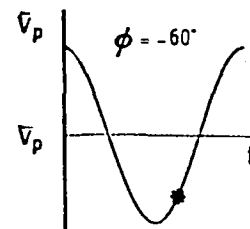
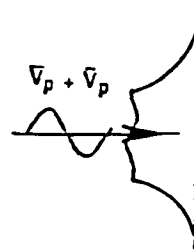


VORTICITY

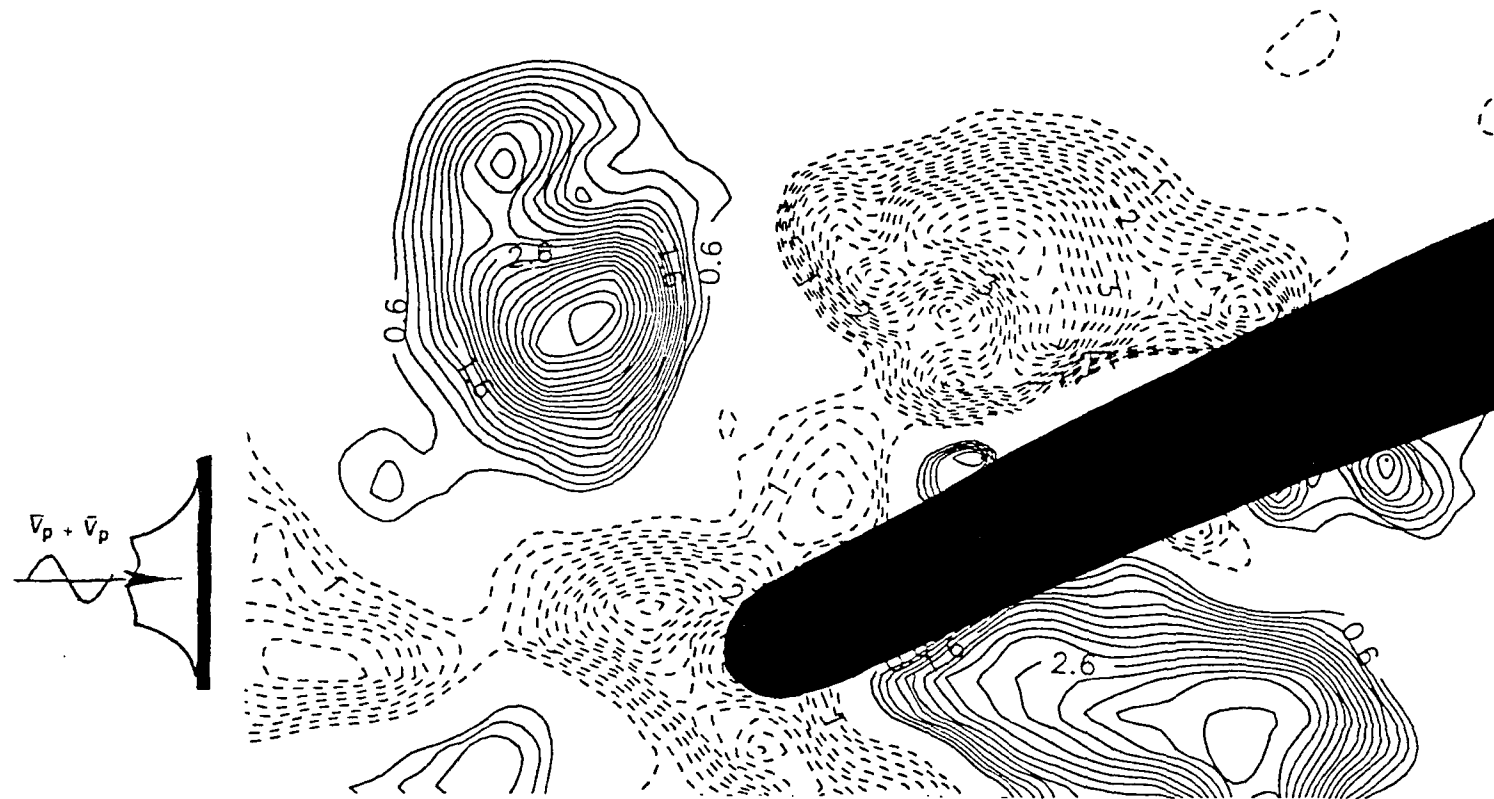


$r_p/r_{bp} = 0.67$

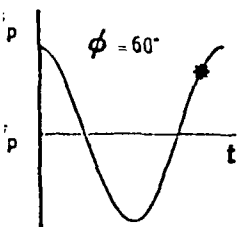
FLOW COEFFICIENT  
 $\phi = 0.183$



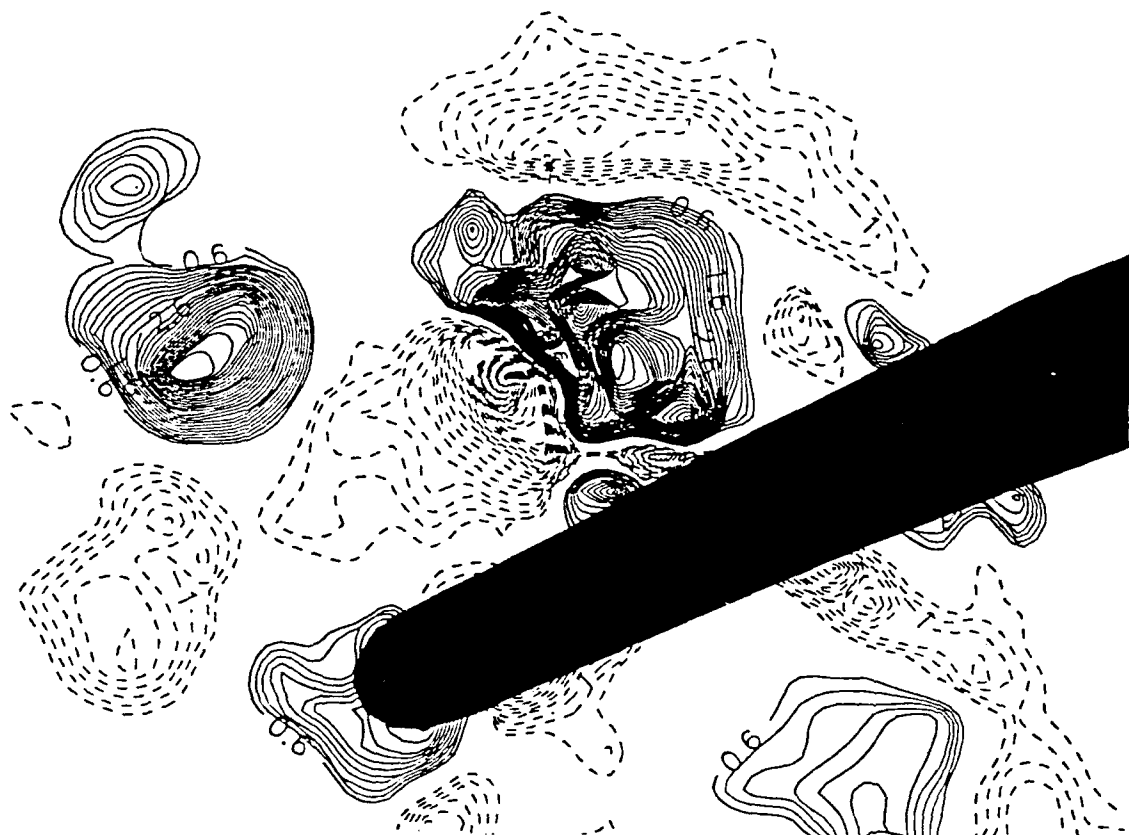
# FLOW STRUCTURE AND PRESSURE SOURCES ALONG A DIFFUSER BLADE



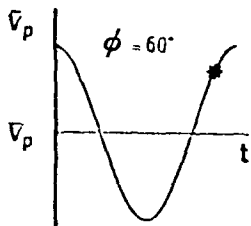
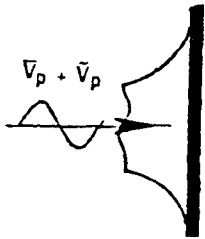
INSTANTANEOUS VORTICITY  $\left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y}\right)$



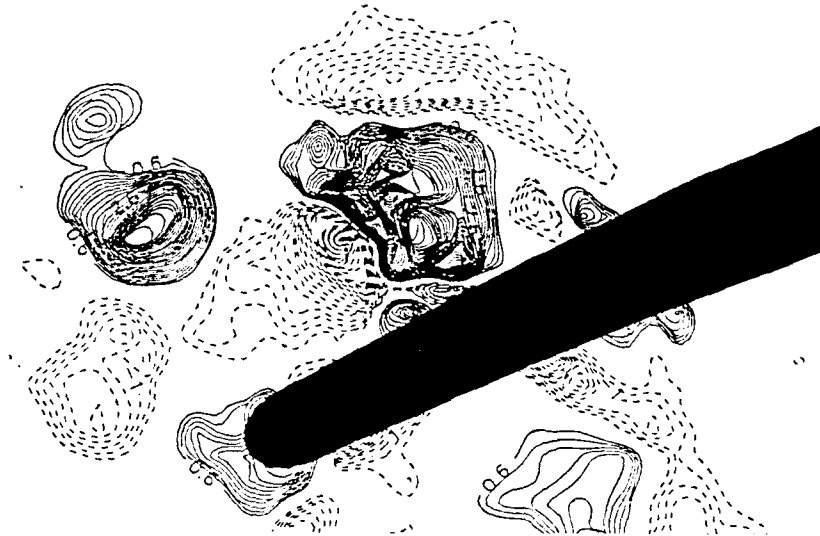
$f_p/f_{bp} = 0.67$



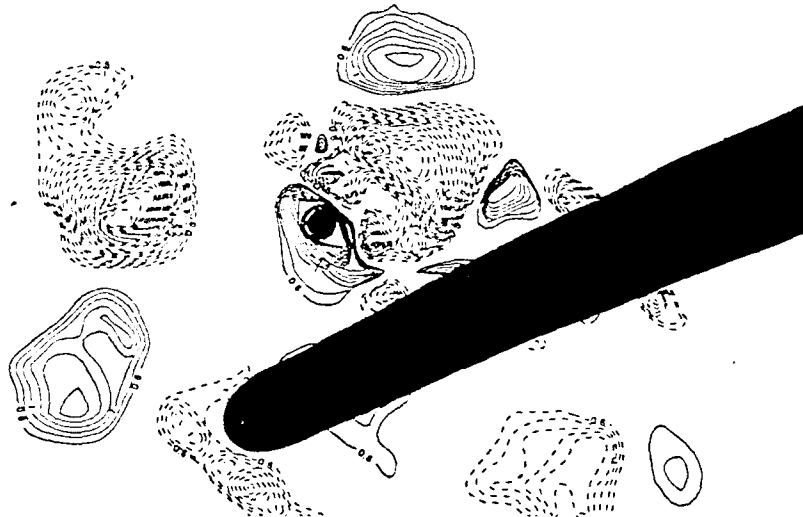
INSTANTANEOUS PRESSURE SOURCE  $\left(\frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x}\right)$



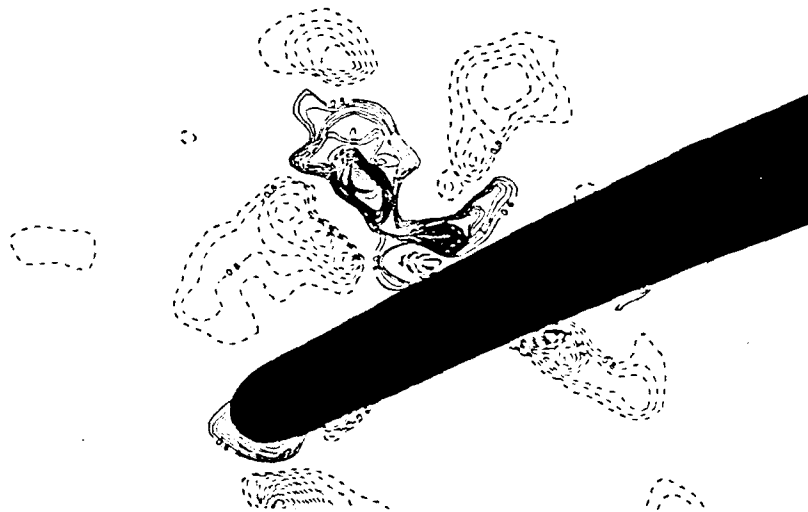
$f_p/f_{bp} = 0.67$



TOTAL INSTANTANEOUS SOURCE  $\left( \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} - \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \right)$



VORTICITY-RELATED SOURCE  $\left( \frac{\partial u}{\partial y} \frac{\partial v}{\partial x} \right)$



RATE-OF-STRAIN-RELATED SOURCE  $\left( \frac{\partial u}{\partial x} \frac{\partial v}{\partial y} \right)$

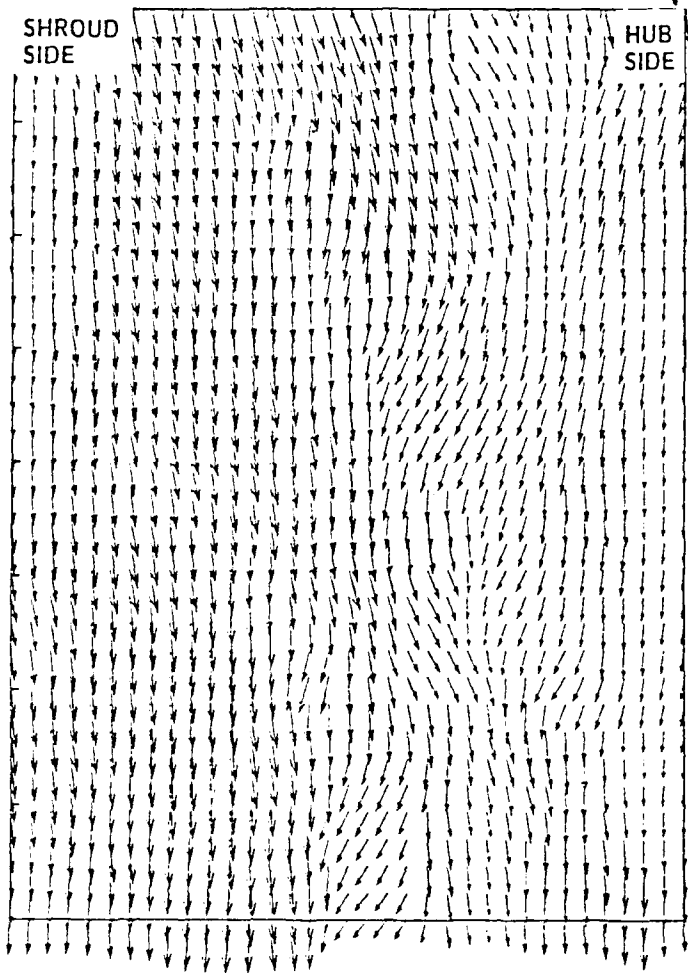
## UNSTEADY FLOW DISTORTION PAST BLADES

- OBJECTIVES
- RESEARCH PLAN
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS
- EXPERIMENTAL TECHNIQUES
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION
  - ✓ LEADING-EDGE
  - ✓ TRAILING-EDGE
  - ✓ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS
  - ✓ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - ✓ ACTIVELY-CONTROLLED PUMPING SYSTEM
- FLOW STRUCTURE IN ACTIVELY-CONTROLLED RADIAL-FLOW MACHINE
  - ✓ OVERALL SYSTEM RESPONSE
  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES IN VANELESS DIFFUSER
  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES ALONG DIFFUSER BLADE OR CUTOFF
  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
  - ⊙ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

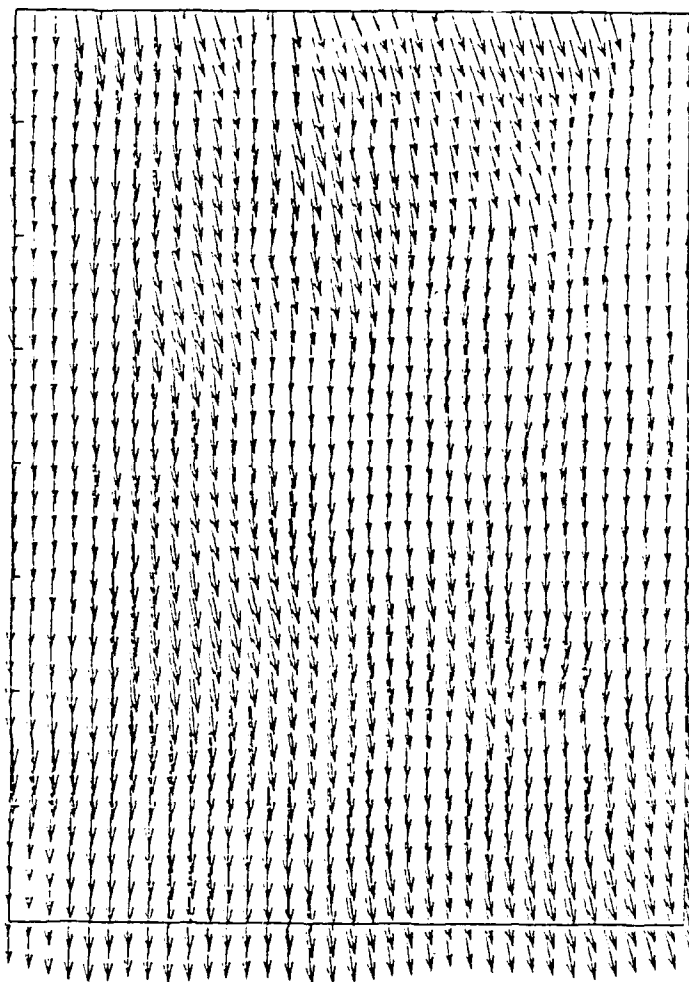
## UNSTEADY FLOW DISTORTION PAST BLADES

- OBJECTIVES
- RESEARCH PLAN
- PRINCIPAL PHYSICAL AND THEORETICAL CONCEPTS
- EXPERIMENTAL TECHNIQUES
- GENERIC CLASSES OF EDGE/SURFACE INTERACTION
  - ✓ LEADING-EDGE
  - ✓ TRAILING-EDGE
  - ✓ LEADING-/TRAILING-EDGE
- EXPERIMENTAL SYSTEMS
  - ✓ GENERIC SYSTEMS FOR LEADING- AND TRAILING-EDGE INTERACTIONS
  - ✓ ACTIVELY-CONTROLLED PUMPING SYSTEM
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  - ✓ FLOW STRUCTURE AND PRESSURE SOURCES AT TRAILING-EDGE OF IMPELLER BLADE
  - ✓ THREE-DIMENSIONAL NATURE OF FLOW STRUCTURE

FLOW THROUGH IMPELLER DIFFUSER SYSTEM:  
INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE

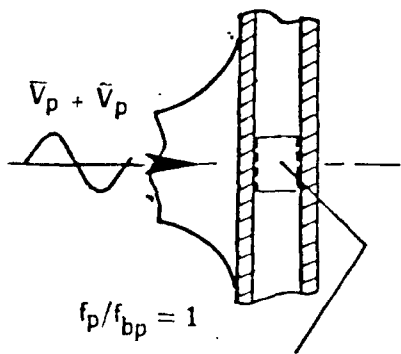


$t = 0$



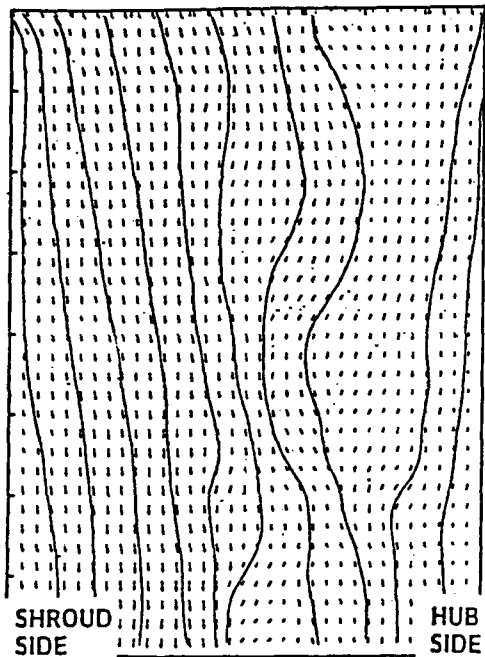
$t = 2/f_{bp}$

INSTANTANEOUS VELOCITY  
IN LABORATORY FRAME



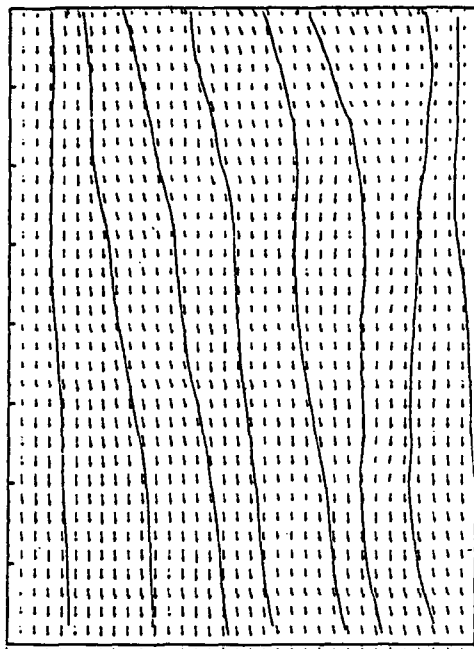
FIELD OF VIEW AT INLET  
OF VANELESS DIFFUSER

**FLOW THROUGH IMPELLER DIFFUSER SYSTEM:  
INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE**

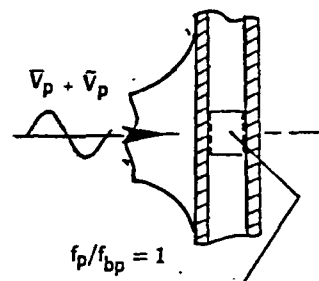


$t = 0$

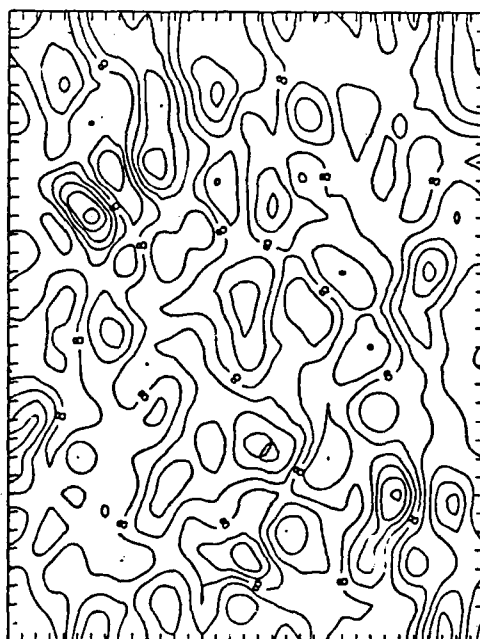
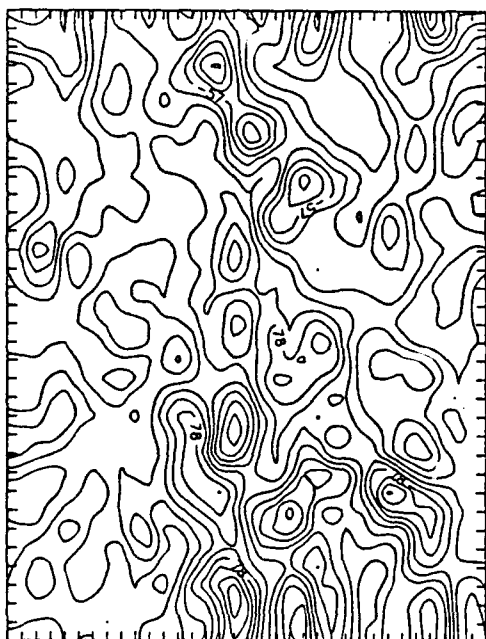
**INSTANTANEOUS STREAMLINES  
IN LABORATORY FRAME**



$t = 2/f_{bp}$

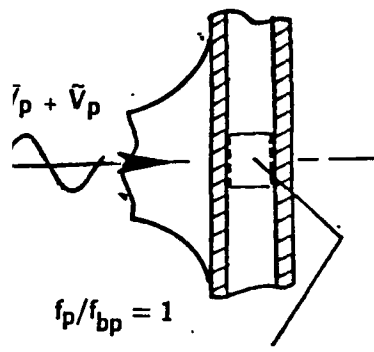


**FIELD OF VIEW AT INLET  
OF VANELESS DIFFUSER**

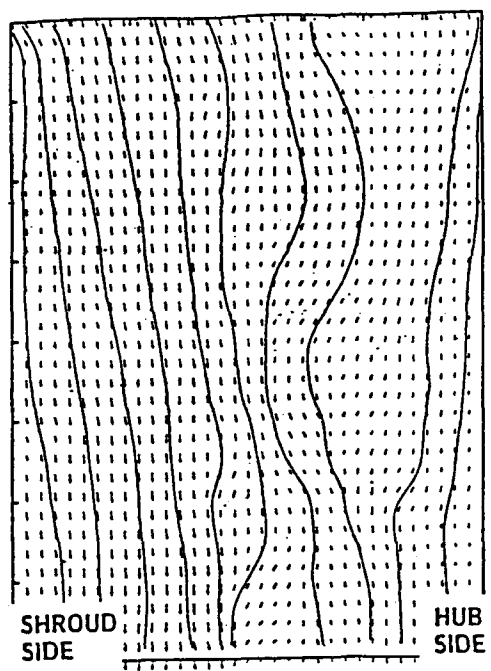


**INSTANTANEOUS DISTRIBUTIONS OF  
STREAMWISE VORTICITY INCLUDING  
ENTIRE RANGE OF POSITIVE AND  
NEGATIVE CONTRIBUTIONS**

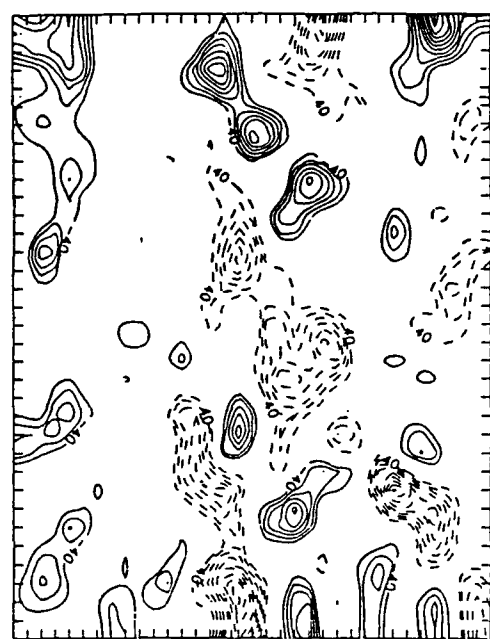
**FLOW THROUGH IMPELLER DIFFUSER SYSTEM:  
INSTANTANEOUS STRUCTURE IN CROSSFLOW PLANE**



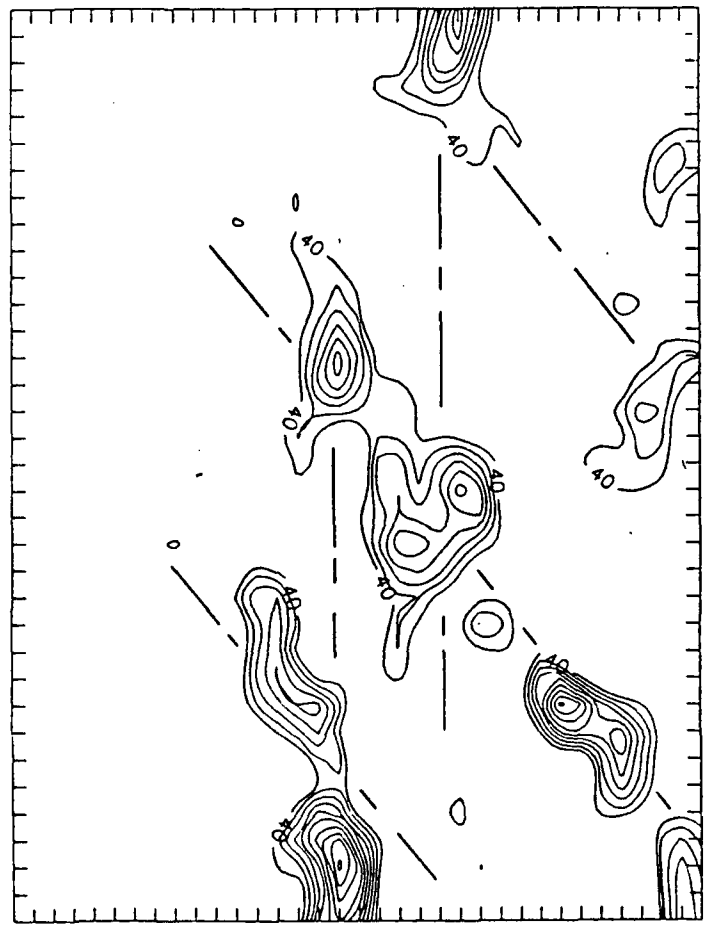
FIELD OF VIEW AT INLET OF VANELESS DIFFUSER



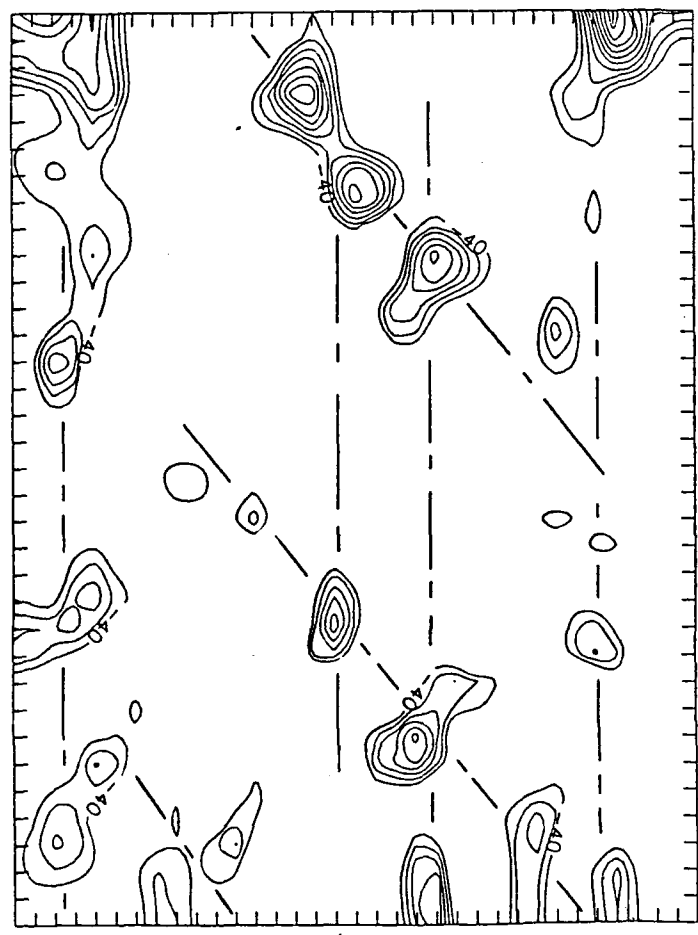
INSTANTANEOUS STREAMLINES IN LABORATORY FRAME



INSTANTANEOUS DISTRIBUTIONS OF STREAMWISE VORTICITY INCLUDING ENTIRE RANGE OF POSITIVE AND NEGATIVE CONTRIBUTIONS



INSTANTANEOUS NEGATIVE STREAMWISE VORTICITY



INSTANTANEOUS POSITIVE STREAMWISE VORTICITY