DOE/MC/29061-96/C0701

CONF-960772--21

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Contract Number:

DE-FC21-92MC29061

Conference Title:

26th International Symposium on Combustion

Conference Location:

Naples, Italy

Conference Dates:

August 1996

Conference Sponsor:

The Combustion Institution

Contracting Officer Representative (COR):

Norm Holcombe

MASTER

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Extension of the Stability of Motions in a Combustion Chamber by Nonlinear Active Control Based on Hysteresis

P. Knoop, F. E. C. Culick* and E. E. Zukoski

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1. Introduction

The notion that hysteretic behavior may occur in combustion chambers probably appeared first in the early Russian work on perfectly stirred reactors (Vulis 1961; Frank Kamenetskii 1969; Denbigh and Turner 1971). In that case the competition between heat losses linear in the temperature of the fluid within the reactor on the one hand and the nonlinear dependence of the heat supplied by combustion on the other, may, under suitable conditions, give rise to three equilibrium states. Figure 1 shows the situation schematically, A, B, and C identifying equilibrium states characterized by equality of the heat loss rate $\dot{Q}_\ell$ and supply rate $\dot{Q}_s$. The intermediate state B is unstable for the following reason. Suppose that the reactor is operating at the conditions labeled B. If a small disturbance is applied causing the equilibrium to shift to state B' having higher temperature, then the supply rate exceeds the loss rate, causing the temperature to rise still further and B' tends to C. Similarly, B'' tends towards A. Similar reasoning shows that A and C are stable-operating points.

When the behavior illustrated in Figure 1 is displayed in the coordinates reactor temperature and temperature of the reactants entering the reactor, the graph of operating points has the form sketched in Figure 2. For a specified temperature of the inflow, there is a range in which there are three operating

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conditions defined by different reactor temperatures. One set of those conditions corresponds to the three equilibrium points labeled A, B, C in Figure 1.

The preceding results are concerned with hysteresis in steady state behavior of a combustion system. In this paper we report what we believe are the first quantitative data establishing the details of hysteresis whose existence in dynamical behavior was reported by Sterling and Zukoski (1987). Moreover, we have demonstrated the new idea that the presence of dynamical hysteresis provides the opportunity for a novel strategy of active nonlinear control of unsteady motions in combustors. The sketch in Figure 3 illustrates the idea in idealized form. Figure 3(a) shows the hysteresis exhibited experimentally for the amplitude (p') of pressure oscillations as a function of the equivalence ratio ϕ in a combustor having a recirculation zone, in this case a dump combustor described in Section 2. The curve in Figure 3(a) is an idealization of the experimental results shown in Figure 5, for example. Tests have normally been carried out with the flow velocity constant. When ϕ is increased from low values, for which the combustor is relatively stable, a value ϕ_1 is reached at which the amplitude of oscillations abruptly grows and the system is observed to be unstable, the point S_1. Further increase of ϕ may cause changes in the pressure amplitude but the system remains unstable.

If then the equivalence ratio is reduced, eventually a value $\phi_2 < \phi_1$ is reached when the oscillations suffer a marked reduction of amplitude, the point S_2. This behavior is interpreted in terms of hysteresis as indicated in the sketch, although presently we have only a tentative interpretation of the physical mechanism underlying these observations. Hysteresis of the sort considered here is associated with a subcritical bifurcation (producing the instability at ϕ_1) followed by an unstable branch of the bifurcation curve and a turning point at ϕ_2

With hysteresis present, there is no well-defined stability boundary such as that one may associate with a linearly unstable system. Figure 3(b) makes the point. Previous work (Smith and Zukoski 1985; Sterling and Zukoski 1987) has shown that the stability of the combustor described in Section 2 is most conveniently displayed with the equivalence ratio and the velocity of the flow at the dump plane as coordinates. Then roughly speaking there is a continuum of hysteresis loops such that globally there appear to be two stability boundaries, one associated with increasing ϕ and one with decreasing ϕ. The points S_1 and S_2 in Figure 3(a) belong to the stability boundaries S_1 and S_2. As the data reported later will show, the width (in units of ϕ) covered by the two boundaries is substantial.

The boundaries S_1 and S_2 are not characterized by the exponential behavior $\left(e^{\pm \alpha t}\right)$ accompanying classical linear instabilities. Experimentally one finds that the transition from stable to unstable behavior occurs in only a few cycles of the oscillation that develops and the growth seems normally to be so uneven that it cannot be consistently identified with an unambiguous value of the growth constant. That distinction offers a possible means of determining experimentally whether hysteresis is present, or whether the system is linearly unstable.

Existence of the hysteretic behavior is the basis for active control in the following way. Suppose that the combustor is initially operating stably, but owing to some disturbance its operating point is translated to the unstable region, point A in Figure 3(b). Then if ϕ is reduced, the operating point moves to the region between the two boundaries, point A' in Figure 3(b). We have shown experimentally that a single pulse of secondary fuel injection can then cause the transition from A' to B' on the branch of the hysteresis loop characterized by substantially lower amplitudes of pressure oscillation. If desired, ϕ can then be increased, maintaining stable operation on the lower branch of the hysteresis loop.

The preceding is intended only as one example of possible active control strategies, all resting on the existence of hysteresis. The possible origin of hysteresis in the combustor studied in this work is the subject of current research. Apparently the mechanism is related to the stability of the shear layer forming the edge of the recirculation zone and subsequent vortex shedding but further work must be accomplished to make our interpretation definite. Sterling and Zukoski (1987) observed two distinct states of vortex shedding, distinguished by widely different strengths of the vortices.

We believe that the presence of dynamical hysteresis in combustors is common; the extent in ϕ over which hysteresis occurs will likely vary considerable with the configuration of the injection and flame stabilization designs. Its existence in the combustor used in this work was implied by data reported by Sterling and Zukoski (1987) but the results found here are the first defining its character and demonstrating the possibility of controlled transitions from the 'unstable' to the 'stable' state described above. Previous work in Russia on liquid rocket combustors (Natanzon and Men'shikova, 1992) has appealed explicitly to the presence of hysteresis to explain some otherwise puzzling behavior of instabilities. However, those researchers did not recognize the phenomenon as a possible basis for active control.

In any event we emphasize that the phenomenon we are concerned with here is hysteresis arising in the dynamics of the combustion system comprising both the combustor with its ancillary parts (inlet, exhaust, etc.) and the combustion processes. Combustion processes alone may or may not exhibit hysteresis, but when combined with the nonlinear behavior of the chamber dynamics, that combination may indeed show the sort of characteristic illustrated in Figures 5 - 7.

2. Experimental Apparatus and Results

The experiments were carried out with the laboratory dump combustor facility at the Graduate Aeronautical Laboratories at the California Institute of Technology (GALCIT). It uses a mixture of compressed methane and air as fuel. The supply system allows selection of variable operating conditions characterized by flow rate and fuel/air ratio. Figure 4 shows the overall layout of the facility. Air and methane are brought together near the entrance of the plenum chamber after first being separately controlled by dome regulators and sonic nozzles enabling mixtures of any stoichiometry ϕ to be used. After mixing, the two flows enter the axisymmetric plenum chamber tangentially. The flow is further mixed and straightened after passing through a series of flat and/or conical screens located within the plenum chamber. The plenum smoothly contracts from a diameter of 15 cm to a rectangular inlet section measuring 2.54 cm high by 7.62 cm wide by 43 cm long.

Near the end of the inlet section, the flow encounters a parabolic shaped insert which further restricts and accelerates the flow as it exhausts into the sudden expansion of the combustion chamber. This sudden expansion, commencing at the "dump plane," serves as a flame holder, anchoring the recirculation region and downstream combustion zone. A spark igniter placed on the chamber floor serves to initiate combustion. Once the combustion is started, the spark is removed and the recirculating hot products immediately downstream of the rearward facing step served to ignite subsequent cold gas mixtures.

A PCB model 106B piezoelectric pressure transducer is used to measure the oscillatory pressure in the combustion chamber. It is mounted in a small water-cooled cavity located on the upper wall of the chamber, 12 cm downstream of the dump plane. The pressure signal is sent to a Pentium microprocessor which serves both for data processing and for controlling the automotive diesel injectors used for the injection of pilot fuel.

2.1 The Region of Operating Conditions Featuring Substantial Bifurcation

Experiments have been carried out to map the region in the plane of operating conditions where a bifurcation occurs. for operating points within this region, for a given set of V_d, ϕ the combustion may be either stable or unstable depending on the history of the process. (Smith and Zukoski 1985; Sterling and Zukoski 1987).

The experimental procedure adopted to determine those limits was to ignite the combustor at the lowest possible ϕ for a given value of V_d. Then the fuel content was gradually increased, leaving the air flow rate unchanged. For some fuel flow rate, the combustion would go unstable. When the fuel content was subsequently reduced, a second value of ϕ would be reached at which the flow makes a transition from unstable to stable burning. This transition point differs from the one for the transition from stable to unstable burning. Figure 5 shows the evolution of the two dominant modes in the spectrum as ϕ is varied.* The rather abrupt transitions from stable to unstable burning and vice versa are clearly apparent. Furthermore, the data show quite good experimental repeatability of the phenomenon; in all cases examined, the hysteresis loop has been traced twice, the two results always being close. We should emphasize that these data are the first we have taken for the active control scheme investigated here. The results are limited and do not answer all questions, but they do demonstrate an important phenomenon.

A compilation of the data for a range of velocities V_d is given in Figure 6. The shaded region, covering a relatively wide range of equivalence ratio, indicates the span of operation conditions under which controllable transitions can be caused from unstable to stable operation, as described in the introduction. Since a large area in the plane of operating conditions is covered, successful implementation of the concept would mean a major extension of permissible operating points for the combustor. It should also be apparent that the proposed new control strategy is restricted to operating points within the shaded region. Operating points to the right of the shaded region cannot be controlled in the manner suggested. See the companion note by Culick and Lin (1996).

2.2 Stability of the branches: Spontaneous Transitions from the Unstable (A) to the Stable (B) Branch

The hysteresis loops shown in Figures 3, 5 and 7 consist of upper and lower stable branches connected by an unstable branch. Operating points on the upper and lower branches are stable but have significantly different qualitative character. On the upper branch, the unsteady motions executed steady limit cycles; on the lower branch the oscillations have very low amplitude in the tests discussed here. As an approximation and convenience

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*The coherent unsteady motions in this combustor normally consist of two dominant modes having frequencies approximately 190 Hz and 235 Hz (Smith and Zukoski 1985; Sterling and Zukoski 1987).

in discussion, we assume that the oscillations are in fact vanishingly small and that the system is linearly stable. On the upper branch the system is linearly unstable but a small disturbance evolves into an approximately steady limit cycle having amplitude represented by the upper branches in Figures 3, 5 and 7. Therefore to simplify the following remarks we refer to the upper (A) branch as unstable and to the lower (B) branch as stable. Figure 8 is the power spectral density for the pressure record taken at point A in Figure 7. The corresponding result for point B of course shows substantially lower values.

In order to characterize further the branches of bifurcation that were observed, we attempted to determine a spontaneous decay rate/natural life time of the branches. For this purpose, the operating points B and A (see Figures 7 and 8) were approached and run for roughly 30 seconds, the maximum run time allowed with the laboratory combustor, due to cooling problems. The pressure record is shown in Figure 9 for the points A and B; in this test, state B is obviously quiet. Although the amplitude of the mode does appear to undergo some fluctuations in operating condition A, there is no spontaneous transition to the state B on the lower (linearly stable) branch. Condition B shows no spontaneous transition to the upper branch A. In principle, the transition from the linearly stable state B to the stable limit cycle at A requires a disturbance of finite amplitude whose value is unknown at this point.

This is an important result, indicating that if the transition $A \rightarrow B$ can be deliberately induced, the combustor should remain stable without further need of external intervention; the equivalence ratio may then be increased to the boundary S_1. For a practical propulsion system, for instance, this provides the basis for a feasible and simple controller that might be added without much technical difficulty.

2.3 Induced Transitions from the Branch A of Stable Limit Cycles to the Linearly Stable (B) Branch

Using a pair of automotive diesel injectors, powered by a custom built circuit, short bursts of CH_4 were injected into the recirculation zone in the wake behind a rearward facing step, referred to hereafter as the flameholder. The injectors and ancillary apparatus are shown in Figure 4. Two locations of the injection slit have been tried, shown in Figure 10. In the tests reported here, the injection system was arranged to provide a train of pulses whenever the oscillating pressure exceeded some chosen amplitude. Pulsed injection ceased when the instantaneous pressure fell below the threshold value. Thus, although transitions could be induced with as few as two pulses, the number of pulses was not controlled. Significant improvements of the injection apparatus are in progress.

The parameters varied were the overall fuel quantity, the pulse width, and secondary fuel flow rate, related by

$$\Delta m = \dot{m}_{CH_4} \Delta t \qquad (1)$$

For a fixed flow rate of CH_4, the pulse width Δt was varied, with the operating conditions those of the tests for Figures 7 and 8. When $\dot{m}_{CH_4}$ was as low as $10\, mg/s$ in the tests carried out to date, the transition in question could be induced. Figure 11 shows that when $\dot{m}_{CH_4} \approx 25\, mg/s$ the total pulse width needed to generate the transition is about 30 ms, corresponding to about 6 cycles of the oscillation at 200 Hz. In all such tests, the motion remained at low amplitude after the transition had been induced. The frequency requirement on the injectors is therefore greatly reduced compared to the conventional control approaches which involve out-of-phase pulsing at the frequency of the instability to be controlled. To confirm that this wasn't a special case, the similar transition was induced for other operating points. Note, as remarked at the beginning of Section 2.2, the motions in a state on the lower branch are not strictly steady, but have much reduced amplitude. The oscillations observed in the lower branch of the hysteresis loop may in fact be driven by random sources of noise in the system (Culick et al 1991; Burnley 1996) and therefore lie outside the matters considered here.

The above experiment was repeated using the flameholder with secondary injection into the upstream boundary layer, Figure 10(b). Similar results were obtained, the transition $A \rightarrow B$ being achieved with two or three pulses of secondary fuel.

2.4 Triggering: Induced Transitions from the Linearly Stable Branch B to the Branch A of Stable Limit Cycles

A question to be answered is: can the process described in Section 2.3 be reversed? That is, can a 'hard excitation' be generated by a sufficiently large disturbance causing the linearly stable system to execute a limit cycle? The lower branch of the hysteresis loop is apparently very stable indeed. Attempts to induce the transition $B \rightarrow A$ using essentially the same pulses producing the transition $A \rightarrow B$ have not succeeded. Manual bursts of methane for two different flow rates were injected to disturb the combustion. In neither case did the system become unstable. Presumably a sufficiently large pulse will in fact produce the transition but this assertion has not been proved experimentally.

3. Concluding Remarks

Although the idea of taking advantage of a hysteresis loop for exercising active control of a system is not new (see, for example Fu 1988; and Abed, Houpt and Hosny 1993), application to a combustor is novel. The results reported here are the first showing unambiguouly the presence of hysteresis in an unstable combustion chamber. Until now, therefore, there has been no basis for considering this type of nonlinear control strategy.

One important practical reason for pursuing application of a nonlinear control strategy is the following (see also Culick and Lin 1996). It is generally the case that the proportion of combustion energy required to excite and sustain combustion energies is an extremely small part of the energy involved in steady operation of the particular device in question. It seems that the results reported to date for control of combustion instabilities by using essentially linear methods have also involved quite substantial parts of the energy release. For example, often the amount of fuel modulated or the flow of secondary fuel injected, carry relatively significant amounts of energy. The results reported here suggest possibilities for control with power requirements closer to the levels intrinsic to the instabilities being controlled.

We believe that the phenomenon of hysteresis demonstrated with this work is in fact likely to be found in many - possibly all - combustors in which flame stabilization is accomplished with a bluff body or similar flow. Its significance probably depends on the geometry and flow conditions in the combustor. Another example has been discussed by Dubinkin, Natanzon and Cham'yan (1978) and Natanzon and Men'shikova (1992) for a liquid jet injector of the sort used in liquid rocket engines. Presently work is progressing to determine more precisely the physical processes responsible for the hysteresis. We believe that in the present case, the two branches (A and B in Figure 7) are associated with two different forms of the shear layer and vortex shedding from the recirculation zone. (Smith and Zukoski 1985; Sterling and Zukoski 1987)

Acknowledgments: This work was supported in part by the California Institute of Technology; partly by ENEL (Dr. Giancarlo Benelli, Program Manager); and partly by the Air Force Office of Scientific Research, AFOSR Contract No. F49620-95-1-0272 (Dr. Mitat Birkan, Program Manager); and partly by the Department of Energy Grant DE-FC21-92MC2906 (Dr. Daniel Fant, Program Manager). The authors have benefited from conversations with Professor Richard Murray and also thank Sudipto Sur, Windsor Lin and Giorgio Isella for their help in carrying out some of the experimental work.

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Figure Captions

Figure 1.	Heat supply and heat loss curves for a generic flow-through reactor.
Figure 2.	Hysteresis in temperature of a generic flow-through reactor.
Figure 3.	Hysteresis of pressure oscillations and its influence on the apparent stability boundary of a combustor.
Figure 4.	Schematic of the laboratory dump combustor with control facility.
Figure 5.	Hysteresis for the on-set of combustion oscillations when ϕ is varied. $V_d \approx 28\, m/s$. The two graphs show the Fourier coefficients of the two main modes as they change when ϕ is varied. The hysteresis loop is traced twice in the experiment.
Figure 6.	Region of the occurrence of bifurcation and hysteresis.
Figure 7.	Hysteresis loop for $V_d \approx 24.1\, m/s$. The ordinate shows the amplitude of the dominant mode at 236 Hz. Points B and A are defined on the stable and unstable branch respectively.
Figure 8.	Power Spectral Density for point A in Figure 7.
Figure 9.	Operating conditions B and A (cf. Figure 7), both corresponding to the same operating point ($V_d \approx 24.1\, m/s, \phi = 0.8$), are run for an extended period of time. No transitions between the two are observed.
Figure 10.	Flameholders with secondary fuel injected (a) at the dump plane and (b) into the upstream boundary layer.

Figure 11. Induced transition $A \rightarrow B$ with $\dot{m}_{CH_4} = 25\, mg / s$ for two pulse widths.

FIG. 1

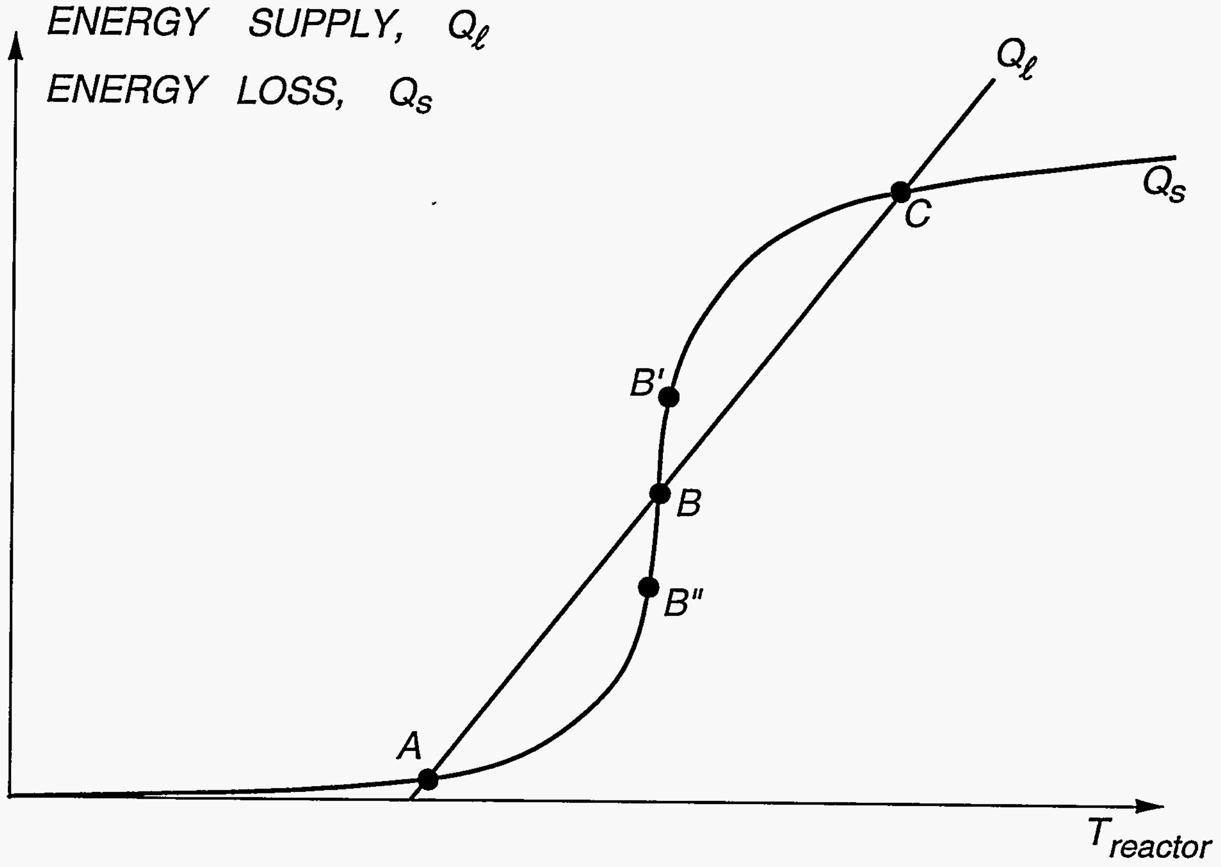


FIG. 2

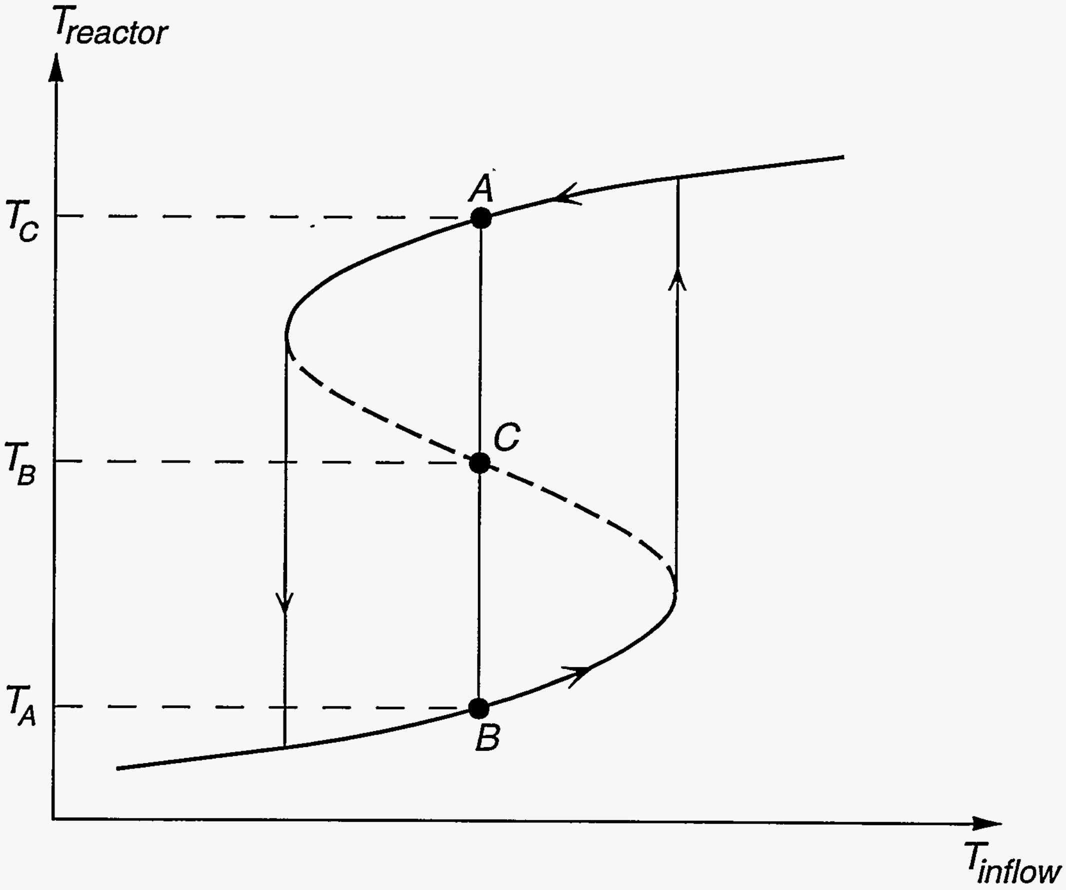
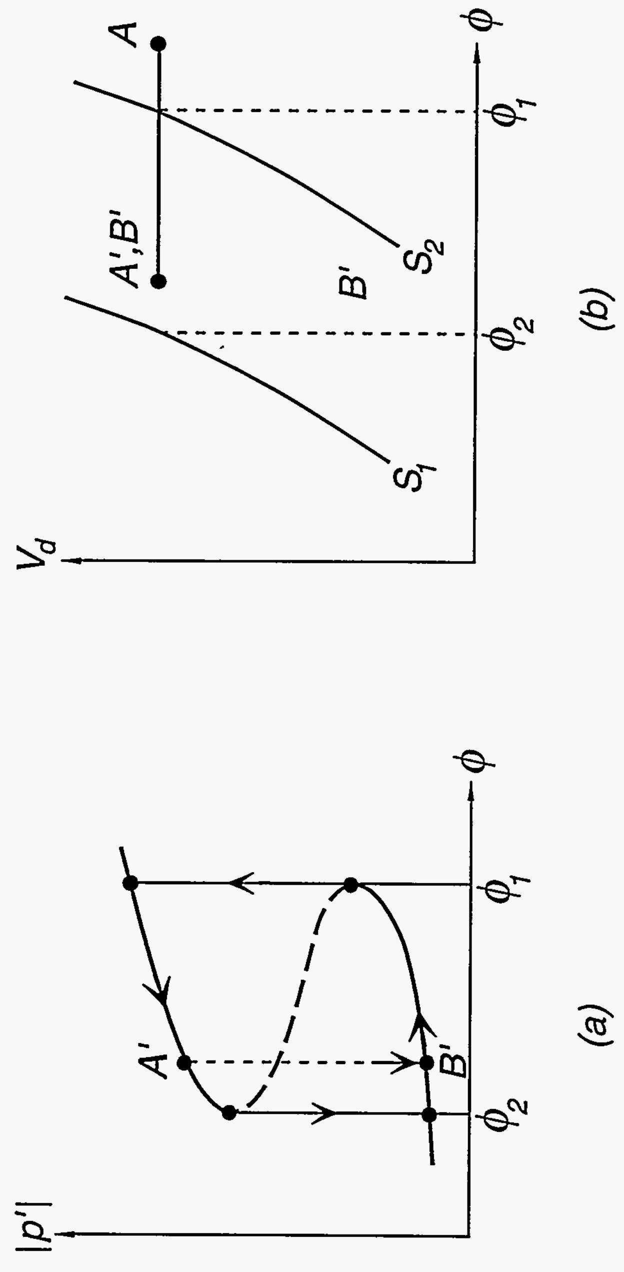


FIG 3

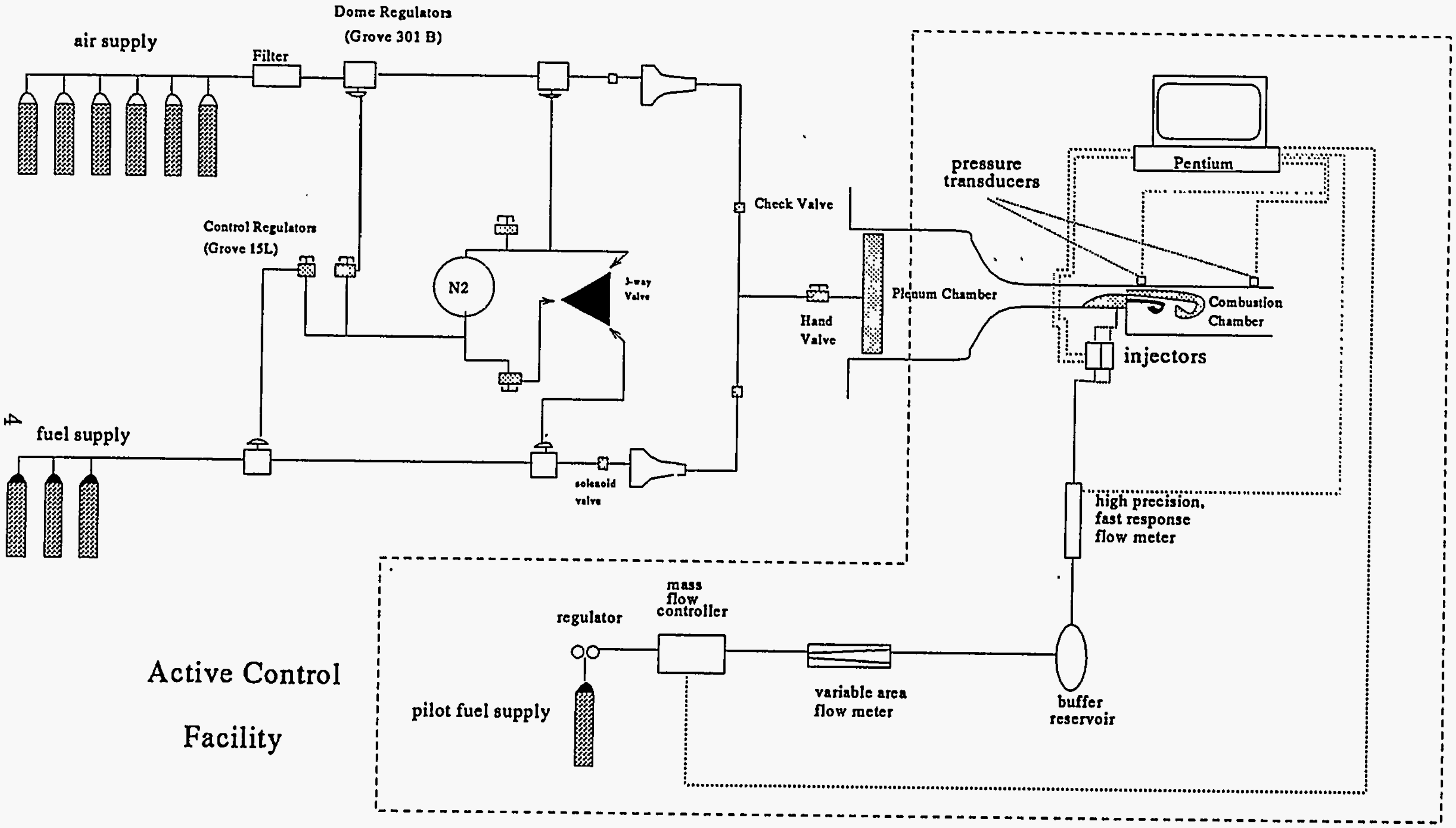
3



(a)

(b)

FIG 4



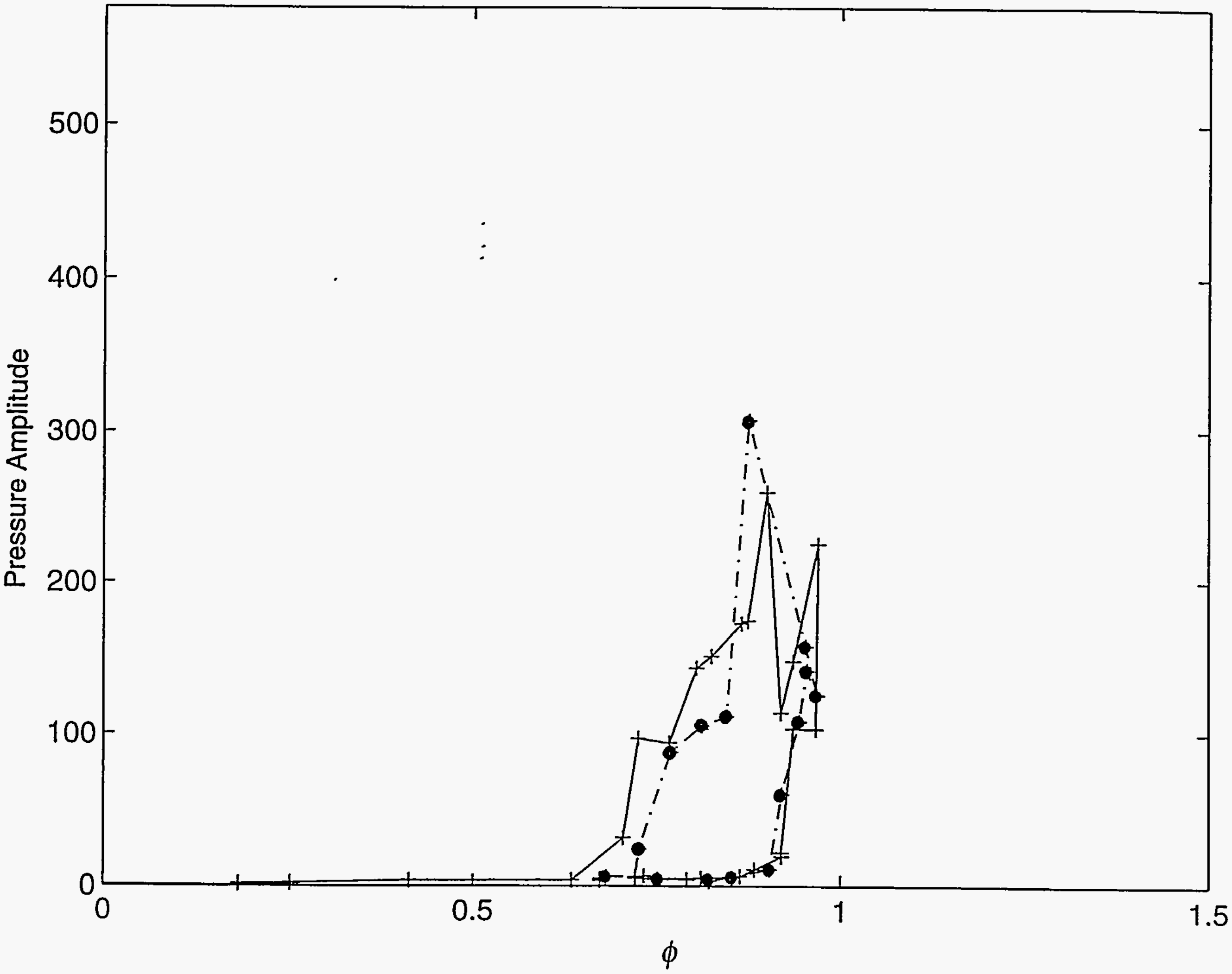
Active Control

Facility

17

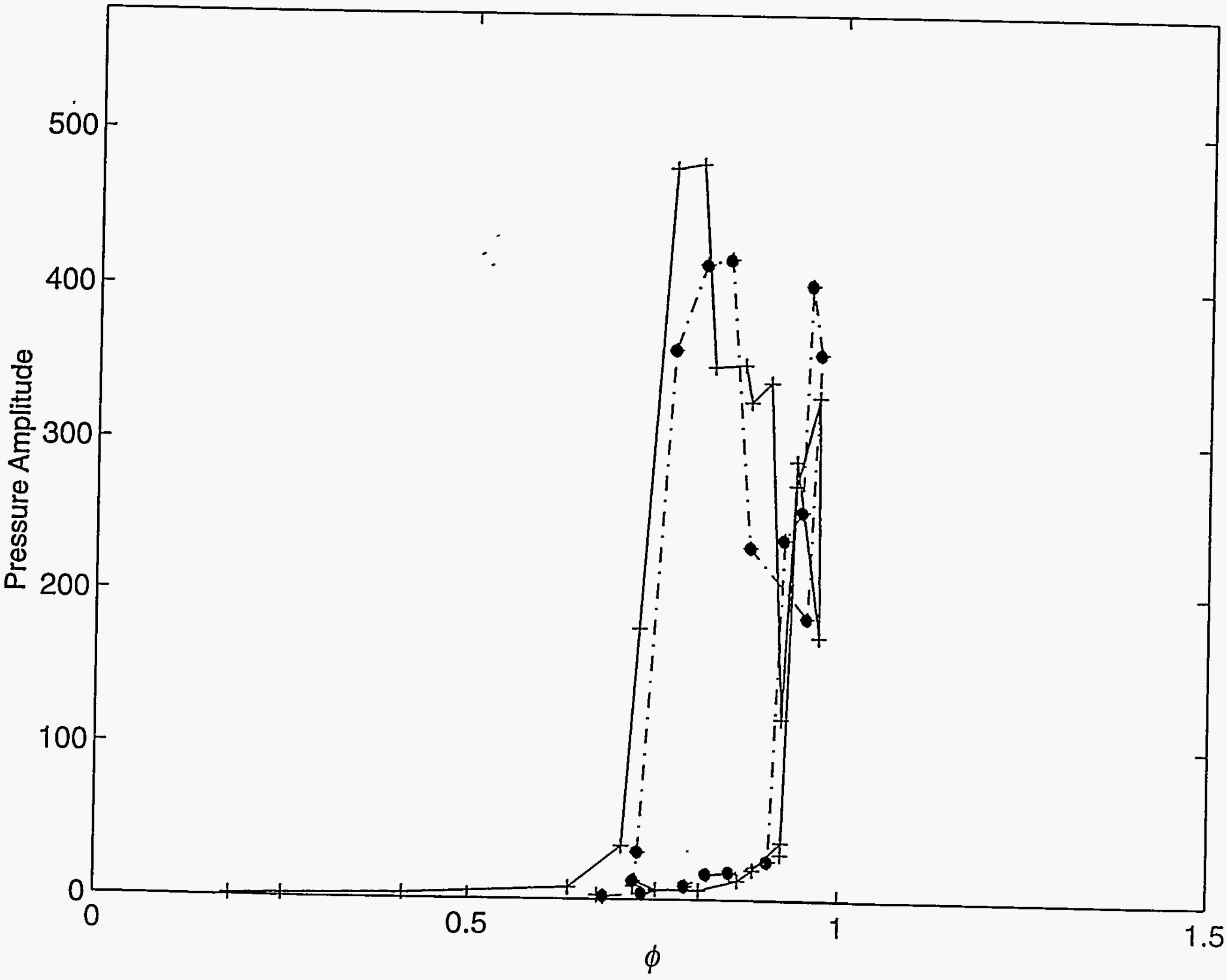
FIG. 4

5(a)



(a) 192 Hz

5(b)



(b) 234 Hz

FIG. 6 ✓

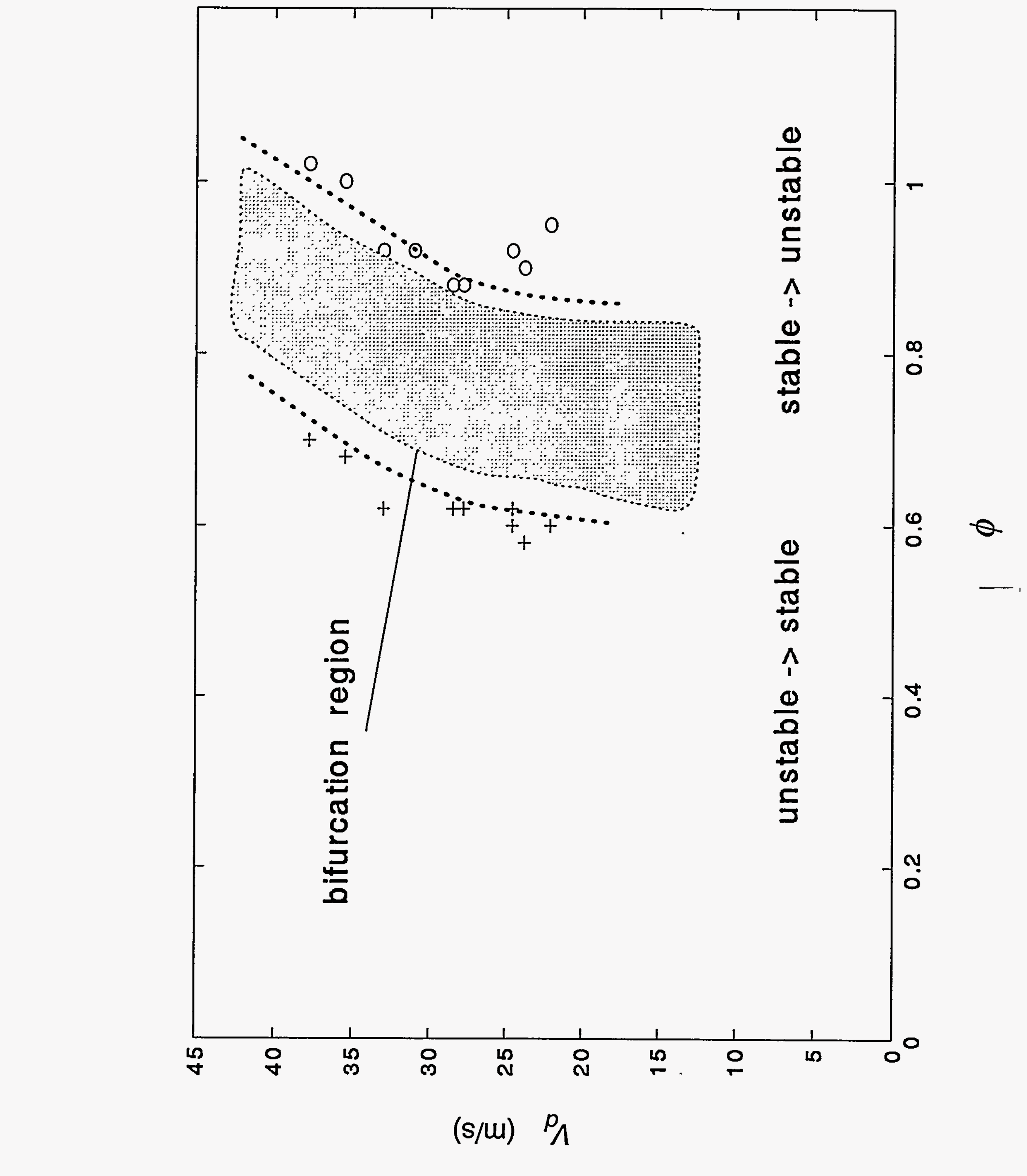
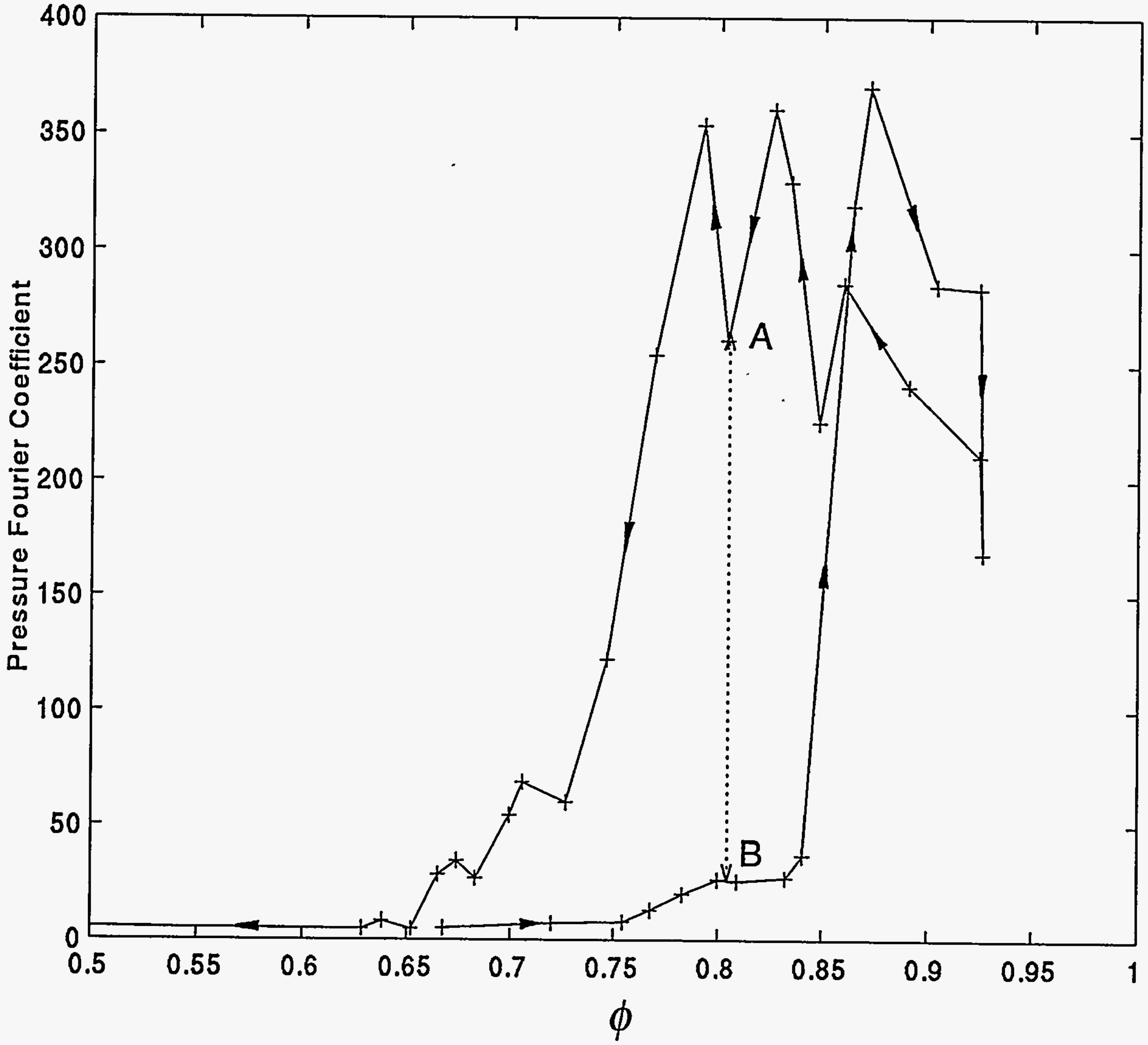

bifurcation region
unstable -> stable
stable -> unstable
V_d (m/s)
ϕ
0
5
10
15
20
25
30
35
40
45
0
0.2
0.4
0.6
0.8
1

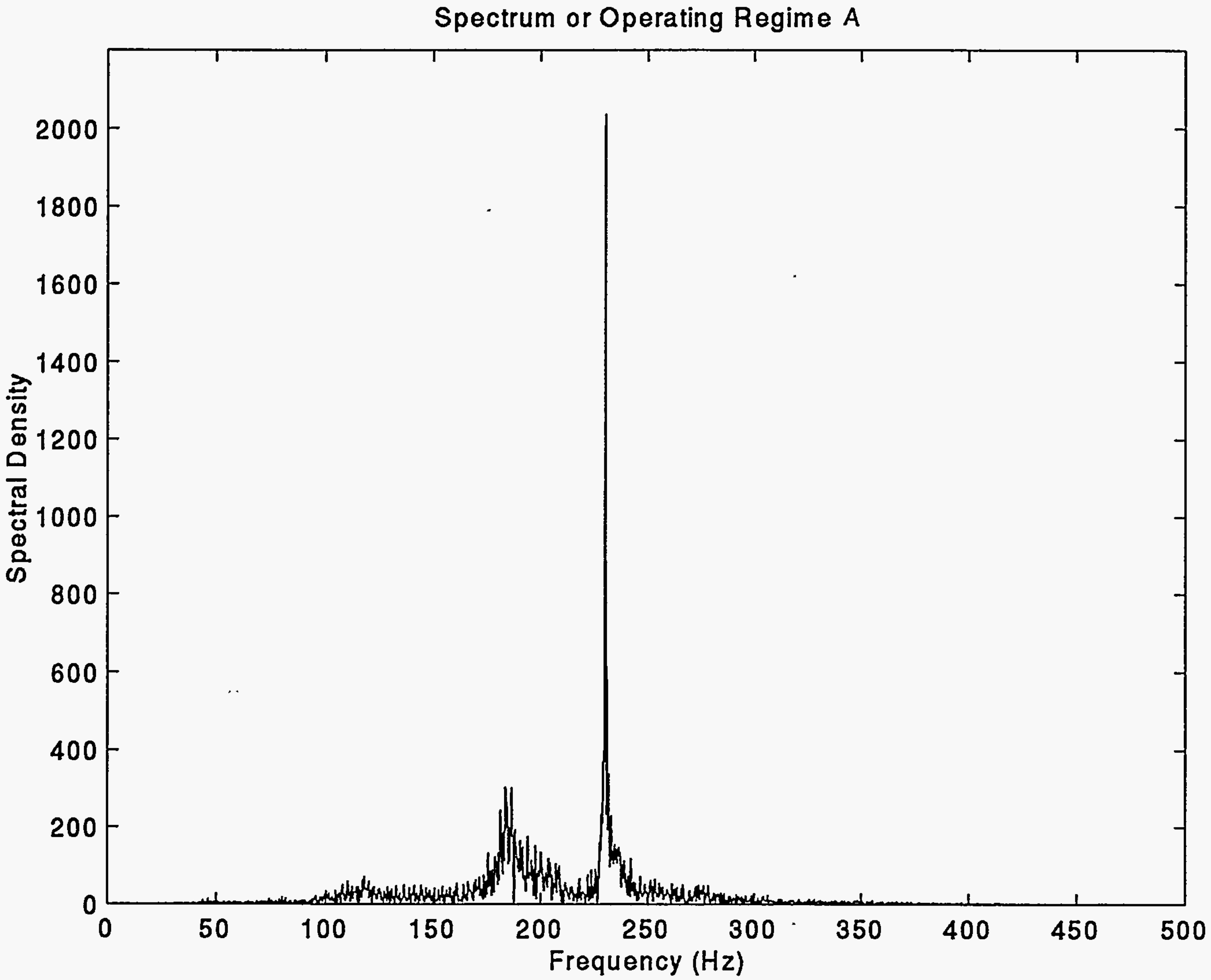
FIG 6

FIG. 7 ✓



400
350
300
250
200
150
100
50
0
Pressure Fourier Coefficient
0.5
0.55
0.6
0.65
0.7
0.75
0.8
0.85
0.9
0.95
1
ϕ
A
B

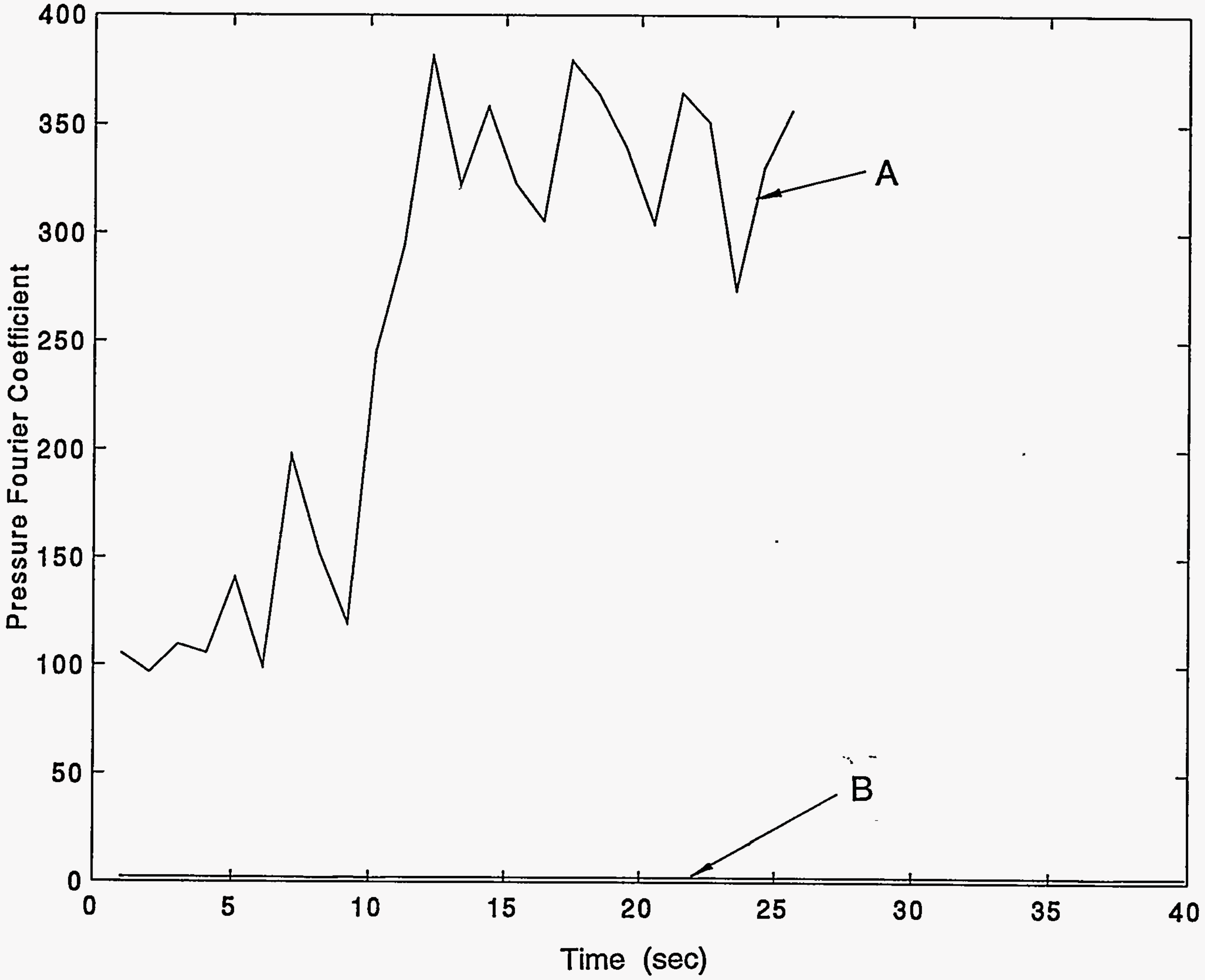
FIG. 8



Spectrum or Operating Regime A
Spectral Density
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0
50
100
150
200
250
300
350
400
450
500
Frequency (Hz)

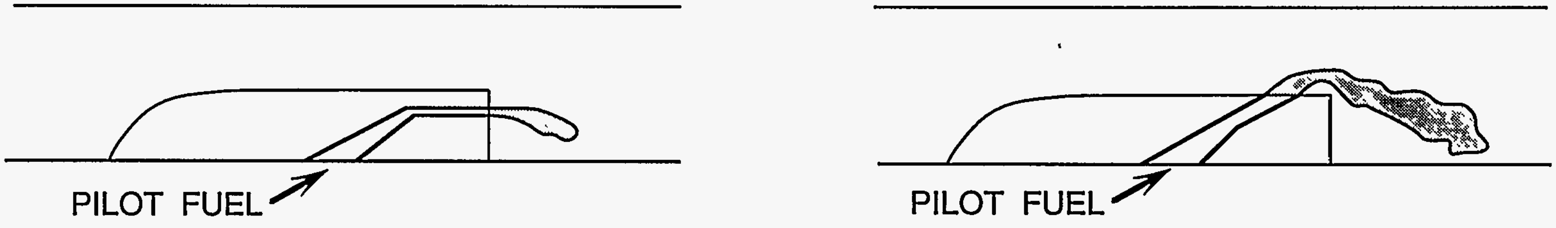
(b)

FIG. 9



Pressure Fourier Coefficient
0
50
100
150
200
250
300
350
400
Time (sec)
0
5
10
15
20
25
30
35
40
A
B

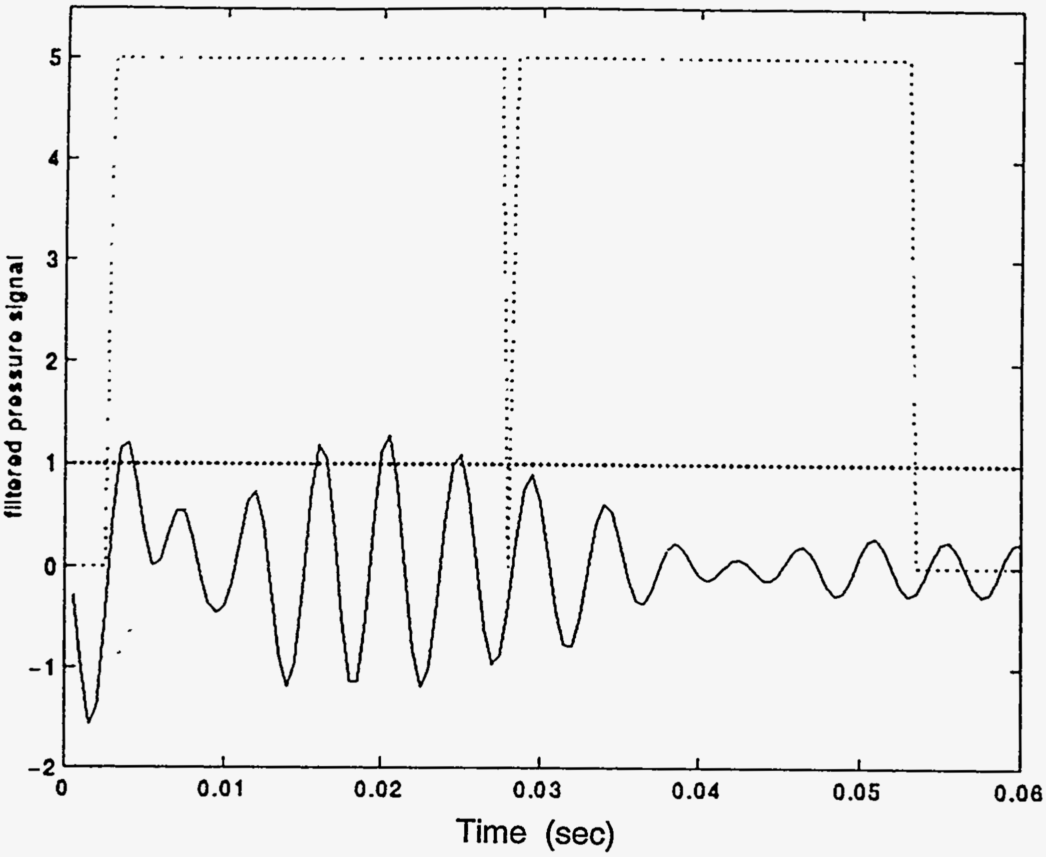
⑩



(a) (b)

FIG. 10

FIG. 11:



(b) Δt = 25 ms