INTERACTIONS BETWEEN ACOUSTICS AND COMBUSTION

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ABSTRACT

Combustion oscillations and instabilities occur in many practical systems such as power plants, ramjets, jet engine afterburners,rocket motors. These phenomena are extremely troublesome as they lead to large amplitude vibrations, enhanced heat-transfer to the combustor walls, structural damage of components and in extreme cases total loss of the system. Mechanisms involved in combustion instability are complex and diverse. Despite a large amount of research, these mechanisms are far from being completely understood. In many situations acoustic interactions play a determining role in the unstable combustion process. Many studies concern the acoustic features of the non-steady process. However, until recently much less information was available on the fluid dynamics of acoustically coupled instabilities. Recent experiments have yielded new insights on the nature of the process. It has been found that in many circumstances the flame front exhibits large scale motions, identifiable patterns and coherent vortex structures. Acoustic waves interact strongly with the combustion region, modifying the instantaneous flow field and changing the mean flame structure. This experimental evidence is reviewed in the paper. Finally control methods of combustion instabilities are presented. Techniques based on active control are more precisely described because of the large number of recent and interesting studies performed in this field.

I. GENERAL INTRODUCTION

Acoustic interactions leading to combustion instabilities occur in many practical systems such as ramjet engines, afterburners rocket motors, industrial furnaces etc... These instabilities induce large oscillations of the flow parameters and have many consequences :

- the performance of the combustion system is modified
- mechanical vibrations are generated leading to increased structural strain
- noise emission is enhanced
- heat transfer is augmented and local overheating may be induced
- flashback extinction or blow-off phenomena may affect one or all flames
- electronic systems controlling combustion may fail due to high vibrations or temperature levels and lead to the loss of control of the system.

Combustion instabilities have been studied extensively during the last fourty years, mainly in the aeronautical and space propulsion domain. The first general conclusion of these studies is the large variety of instability mechanisms and the necessity of a one by one analysis. The diversity of combustion instabilities is qualitative (i.e. low, medium and high frequency) but it is first of all, the consequence of the physical phenomena involved : turbulence, acoustic modes, hydrodynamic instabilities, thermodiffusive effects, chemical kinetics.

For a proper perspective we will begin this review with a classification of instabilities based on the ideas of Barrere and Williams (1968) and Putnam (1971). Three main classes can be defined :

1) System instabilities involving the whole system from the reservoir to the exhaust. As their characteristic wave length is high, the frequency of these modes is low (typically less than 200 Hz in aircraft engines). A well known example is the POGO instability where the structural vibrations of a rocket couple with the combustion oscillations in the chamber.

2) Chamber instabilities : these modes are generated by mechanisms occuring in the combustion chamber only. Their frequency is higher (300 Hz to 10 KHz).

3) Intrinsic instabilities independant of the chamber geometrical configuration. These oscillations are intrinsic functions of the flame structure and depend on transport and chemical phenomena occuring inside the flame zone.

This classification, based on the characteristic lengths involved is not the only possible way of describing combustion instabilities. It is also useful to consider physical mechanisms involved in a given combustion instability. Generally speaking, combustion instabilities are the result of a resonant interaction between (at least) two oscillatory mechanisms occuring in the system : an excitation mechanism and a feedback effect. In

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combustion systems, the mechanisms that may be considered as potential excitation mechanisms are: turbulence, hydrodynamic perturbations, chemical effects, thermodiffusive phenomena etc... which may all produce oscillations but lead to combustion instability only if they couple with some resonant feedback effect. This feedback effect must be induced by the excitation mechanism and act on the perturbation.
As an example, suppose that vortices are formed in a combustion chamber as a consequence of acoustic transverse velocity oscillations (acoustic sloshing). If these vortices entrain fresh gases which burn after a certain delay, a feedback effect may be induced by the associated pressure pulse emitted by the burning vortex. This wave propagates upstream and triggers another vortex shedding. If certain phase conditions are satisfied, the process may be amplified and lead to combustion instability. This is a typical acoustic instability of the kind investigated by Rogers and Marble (1956). It usually features a high frequency sound radiation and is designated as "screech" in the jet propulsion literature. Because this instability has generic characteristics it is described in more detail later on. This simple example reveals an important feature of combustion instabilities: the feedback process must be able to relate upstream to downstream regionss of the flow. As a consequence physical mechanisms like convection or diffusion do not constitute adequate feedback paths. In practical situations, structural vibrations and acoustic waves are the most common feedback processes. This review will be centered on acoustic instabilities. Structural vibrations effects are important in many situations (for example for the POGO effect in rockets) but they will not be considered here. This review will be centered on acoustic instabilities. A particular class of instability is obtained when the acoustic wave and the heat released by the combustion are strongly coupled and lead to the formation of a shock wave. In some cases, hydrodynamic instabilities appear to be the predominant excitation mechanism but it should be kept in mind that the feedback path is generally linked to the pressure variations in the system, even if acoustic waves are not explicitly apparent. The thermodiffusive instabilities of laminar flames are one exception to this rule. In this special case : perturbations are not convected because there is no mean flow and an unstable perturbation can grow on the flame front and lead to instability without any feedback effect.

I 1. System instabilities

System instabilities are usually found in the low frequency range. They involve the entire combustion system that is, the storage tanks, the supply lines, the combustion chamber, the gas exhausts. Characteristic lengths associated with system instabilities and the corresponding wavelengths are usually large compared to the dimensions of each component of the combustion system so that each of these elements can be considered and modelled as a compact element of a vibrating system (Putnam 1971). For example, the pressure in the combustion chamber will be supposed to be a function of time only (and not of the location of the chamber point where it is measured). Acoustical phenomena are often involved in system instabilities but their analysis is largely simplified by considering only longitudinal plane waves or lumped parameter components. Although system instabilities may appear in all combustion systems, they are most often encountered in rockets and large scale powerplants. Typical frequencies and amplitudes of rocket system instabilities are in a range of 40 to 200 Hz pressure (Barrere and Willimas 1968, Barrere and Corbeau 1964, Harrje and Reardon 1973). These modes are strong and have, in most cases, destructive effects. Theoretical studies based on the sensitive time lag concept (Crocco 1965, Tsien 1952, Marble and Cox 1953, Cheng 1954) allow satisfactory prediction of instability frequencies but not of amplitudes.
Recent advances in experimental methods have allowed studies of the response of reacting flow fields to system instabilities in the case of gaseous combustion. Campbell, Bray and Moss 1983 and Lee 1983 used schlieren visualizations of the flame front movement in a laboratory afterburner to study a system instability designated as "buzzing". In their configuration, a premixed gaseous flame is stabilized in a rectangular duct by a V-gutter obstacle.
Under certain operating conditions a strong instability at 60 Hz appears ("buzzing"). Schlieren views of the flame front (Fig. I 1) reveal a periodic destruction and renewal of the whole flame pattern . While this mode corresponds to a low frequency oscillation, the response of the flame is quite complex. This behavior is the first difficulty encountered in the analysis of system instability : even if pressure is supposed homogenenous in the combustion chamber, a complex fluid flow pattern develops in the flame region and prevents any simple modelling of the combustion chamber. Moreover, secondary mechanism like vortex shedding or acoustic modes (at higher frequencies than buzzing) may also play a role in the dynamics revealed by the schlieren photographs. Picture 4 in Fig. I 1 shows that small scale structures are superposed to the mean "buzz" structure. The effect of these perturbations is not yet clarified.

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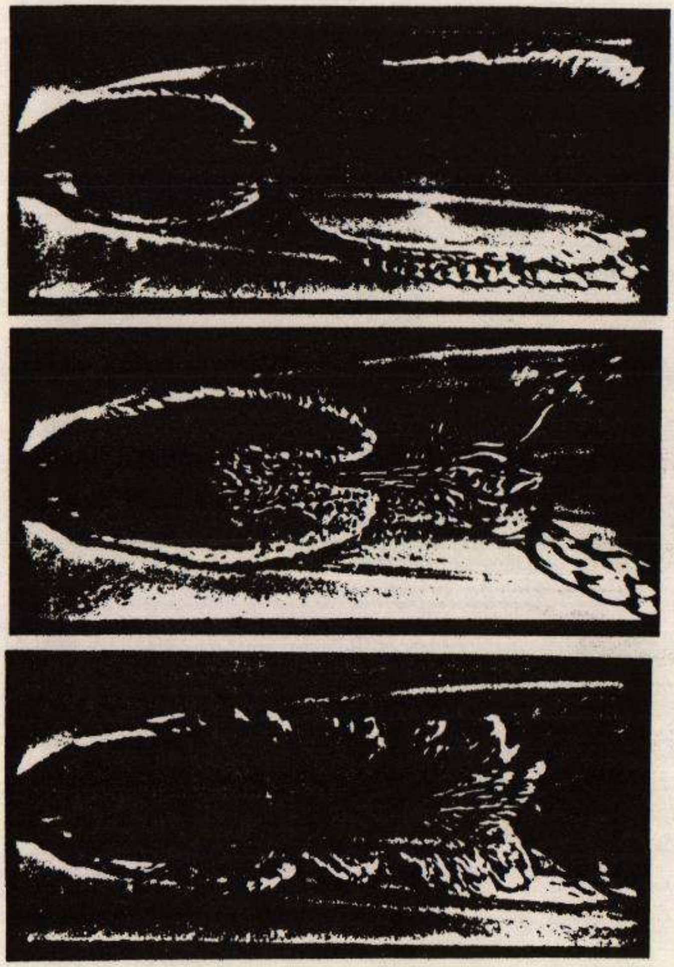

Fig. I 1: Visualization of buzz (Campbell et al 1983)

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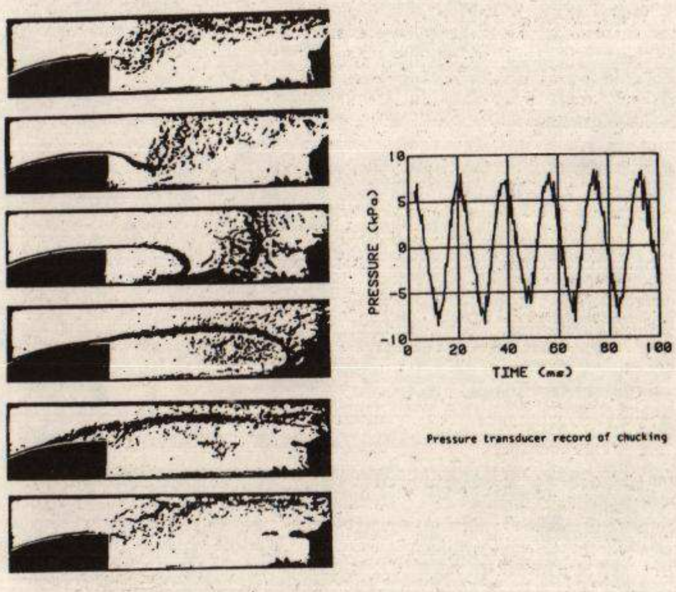

Fig. I 2: Visualization of chucking (Keller et al 1981)

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Another example of system instabilities of a gaseous combustor has been discussed by Keller et al (1981) in the case of a backward facing step combustor. These combustors are geometrically close to ramjets and more generally to many industrial furnaces. They have been the subject of many studies (Marble and Candel 1978, Parker et al 1979, Pitz and Daily 1983, Smith and Zukoski 1985). Dump combustors are characterized by the fact that the flame stabilization is produced by a sudden increase of the duct cross section. In the experiment of Keller et al, this cross section variation corresponds to a backward facing step (it may also be produced by jets flowing into a large cavity (Darabiha et al 1986, Poinsot et al 1987). Hot gases recirculating behind the step (or steps) constitute a continuous ignition source for the fresh gases and allow flame stabilization. Dump combustors exhibit numerous instability modes. One of these modes, studies by Keller et al 1981 and called "chucking" corresponds to a system instability mode at 55 Hz. This mode is the strongest unstable mode of the system and leads to a periodic flash-back of the flame upstream of the stabilizing step (Fig. I 2).

I 2. Chamber Instabilities

Chamber instabilities are generated by mechanisms occuring inside the combustion chamber. In many circumstances, the distinction between system and chamber instabilities is not clear : most chamber instabilities involve mechanisms occuring outside the flame zone. For example, chamber acoustic instabilities in the low frequency range usually correspond to longitudinal modes propagating upstream and downstream of the combustion chamber but their wavelength is of the same order as the chamber dimension and the spatial structure of the pressure perturbations is important. In other words the pressure cannot be assumed to be constant in the chamber as in the case of system instabilities.
Three main classes of chamber instabilities may be distinguished.

(a) Acoustic instabilities
(b) Shock waves instabilities
(c) Hydrodynamic instabilities

I 2 1. Acoustic Instabilities

The most common instabilities are purely acoustic. The frequency of these instabilities correspond to the eigenfrequencies of the chamber. These frequencies scale like the velocity of sound in the combustion gases and like the inverse of the characteristic size of the chamber. The first combustion instabilities reported in the literature are "organ-pipe" acoustic oscillations where the characteristic size imposing the frequency is the chamber length. An early observation of such a mode was made by Higgins in 1877 (see Putnam 1971) in the case of a diffusion flame placed in a tube open at both ends. Higgins indicates that the system produced oscillations and noise for certain lengths of the fuel supply line. This "singing flame" instability has been studied by many authors. Rayleigh (see Rayleigh 1945) was the first to propose a criterion for combustion instabilities and to present an analysis of the singing flame experiment . Review papers on singing flames are due to Richardson (1922), Jones (1945) and Putnam (1971). Typical instability domains are presented in Fig. I 3 (Jones 1945). Experimental results may be simply interpreted with analytical models using two assumptions :
1) The oscillation frequency must satisfy Rayleigh's criterion at the fuel supply line end, which means that pressure and heat release variations must be in phase. An important parameter for this criterion is the time lag between flow and heat release fluctuations. As discussed later, this parameter is a weak point of Rayleigh type models because it is not a result of the calculation but is to be obtained or estimated from experiments.
2) The oscillation frequency must also be an eigen-frequency of the combustion tube. This explains why such modes are called "organ-pipe" oscillations (Putnam 1971). The sound emitted by the flame in the tube has the same frequency as the tube would have in an organ (taking into account the variations of temperature and speed of sound).
These two aspects are clearly related to the excitation mechanism (heat release variations due to velocity changes in the fuel supply line), the feedback effect (acoustic modes of the combustion tube) and the phase conditions between excitation and feedback (Rayleigh's criterion).
Organ pipe instabilities occur in many combustion systems and often exhibits large amplitudes. They have been found in afterburners, ramjets, rockets but also industrial burners like residential heaters of blast furnaces cowpers. A review of organ-pipe oscillation experiments is given by Putnam (1971) and Putnam and Dennis (1954).

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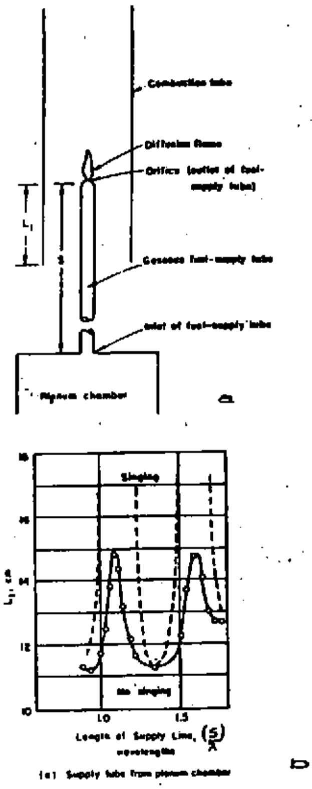

Fig. I 3: The singing flame experiment (Jones 1945, Putnam 1971)

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Organ-pipe oscillations are some of the simplest cases of acoustic instabilities. They are usually associated to longitudinal low frequency standing waves. However, many other acoustic instabilities may be encountered which involve tangential or radial acoustic modes. Travelling waves and spinning modes are often observed. In many industrial combustors the geometry is so complex that it is not possible to follow the classical description of longitudinal, tangential and radial modes. The appearance of acoustic instabilities in practical systems is determined by the characteristic combustion times and the geometrical configuration of the reactive zone. For example, longitudinal modes will be obtained for reactive zones located at one duct abscissa and independant of transverse coordinates while a reactive zone located on the axis of the combustor cavity may possibly excite radial modes. The high frequency combustion instability called "screech" oscillation already mentioned above is a classical example. This instability occurs in afterburners at frequencies greater than 1000 Hz and it has destructive effects on the engine structure. It has been the subject of many experimental and theoretical studies (Truman and Newton 1955, Blackshear et al 1955). The best description of screech was proposed by Rogers and Marble (1956). These authors show that the "screech" instability is the result of an interaction between vortex shedding and the first acoustic transverse mode of the duct (Fig. I 4). In the case of stable combustion, the flame is stabilized by hot gases recirculating behind the flame holder (Fig. I 4a). Under certain operating conditions, alternating vortices are shed from the flame- holder lips at the screech frequency (Fig. I 4b). Rogers and Marble propose the following mechanism for screech :

1) A vortex is formed, due to the sloshing motion induced by the acoustic mode
2) This vortex entrains fresh gases and carriesthe reactants into the hot recirculating wake zone of the flame holder.
3) After a certain characteristic time needed for mixing and ignition, the fresh gases burn and generate a pressure wave which excites the antisymmetric duct mode. This particular mode is favored because the vortices are formed and convected in the neighborhood of the duct walls.
4) This antisymmetric mode triggers another vortex shedding and the cycle is self sustained if certain phase conditions are satisfied.

It is worth indicating that screech is a purely acoustic phenomenon. Vortex shedding is not due to the classical hydrodynamic instability of the wake of the bluff body but to the sloshing velocities at the flame holder lip generated by an acoustic transverse mode. Another interesting feature of screech is the low frequency component induced by the high frequency acoustic mode which reveals the strong non linearities of the phenomenon. Similar high and low frequency combinations are found in other experiments (Zikikout et al 1986).

I 2 2. Shock wave instabilities

In certain combustion systems, heat release mechanisms are strong enough to induce shock waves. If these shock waves have a feedback effect on the combustion process, shock waves instabilities may appear. Such instabilities are usually observed in rocket motors where the chemical reaction is particularly intense (Barrere and Corbeau 1964). In some cases, shock wave instabilities constitute the limit cycle form of an acoustic wave growing without damping effects. They may also be generated by a local detonation or a violent ignition phase. The basic phenomena describing the interaction between a flame front and a shock wave have been reviewed by Rudinger (1958) and more recently by Oran and Gardner (1987).

I 2 3. Hydrodynamic instabilities

Early and more recent experiments reveal the importance of hydrodynamic instabilities and of organized structures in perturbed reacting flows.

In the case of non reactive shear layers, experimental investigations have shown that large coherent structures are intrinsic features of turbulent mixing layers (Brown and Roshko 1974, Winant and Browand 1974). A review of shear layer instabilities given by Ho and Huerre (1984) summarizes many important features. These Kelvin-Helmholtz type instabilities are characterized by discrete oscillation peaks and the formation of coherent structures at frequencies which may be predicted through simple Strouhal rules based on the initial momentum width of the shear layer and the velocity difference between the flows forming the mixing layer. An interesting feature of these phenomena is the downstream evolution of vortices and their possible coalescence and pairing. Even without combustion, experimental results have revealed feedback effects correlating, in a nonlinear fashion, the downstream coalescence of vortices and their initial formation in the initial part of the mixing layer. Laufer and Monkewitz (1980) have proposed feedback laws to relate initial vortex shedding and the feedback effect due to coalescence. Basically, these laws indicate that the initial vortex shedding frequency and the number of

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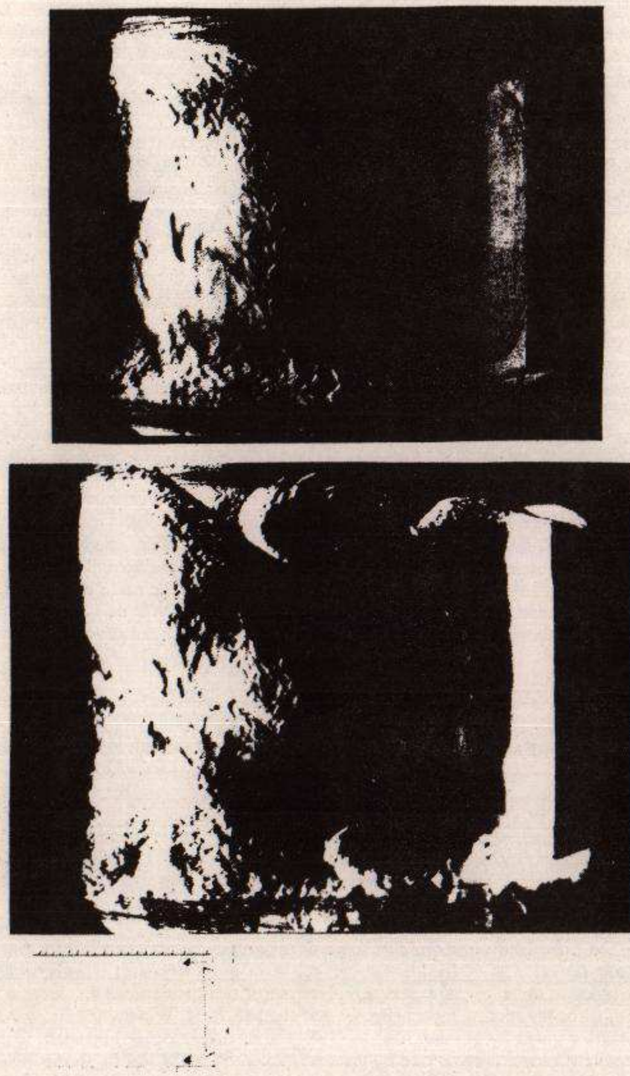

Fig. I 4: Visualization of screech in a simulated afterburner (Rogers and Marble 1956)

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downstream coalescing vortices are adjusting their values so that the sum of the time for convection from the shear layer origin to the merging location and the time for acoustic propagation upstream, back to the shear layer origin be an integer multiple of the merging period (Ho and Huang (1982). A special case of such interactions is obtained in the "edgetone" experiment where a jet impinging on a solid wedge produces a loud tone. Coherent fluctuations shed in the jet "lock-in" with acoustic waves generated by merging vortices impinging on the solid sharp edge and an "instability" appears (Ho and Nosseir 1981). Direct numerical simulation of shear layers and wakes (Grinstein et al 1987, Kourta et al 1987) have confirmed these nonlinear effects and revealed the influence of acoustic waves on vortex shedding and coalescence.
Most reactive flows involve shear regions and it is therefore expected that hydrodynamic instabilities will play an important role in many situations Furthermore, the feedback effect demonstrated in cold shear layers is clearly more important when combustion may take place in vortices and generate large amplitude pressure perturbations. As indicated previoulsly, hydrodynamic oscillations in flames lead to strong instabilities only if they are coupled with an acoustic feedback path. Experiments have shown that hydrodynamic phenomena are indeed, primary mechanisms in certain combustion instabilities (see for example Bray et al 1983).
Blackshear (1956), performed linear stability analysis of reactive shear zones and showed that the results obtained were applicable to certain oscillation modes appearing in stabilized flame experiments. For example, the frequency of some of these modes could be predicted by a modified Strouhal scaling rule However it is important to notice that, in most experiments, hydrodynamic instabilities and purely acoustic instabilities may appear for the same operating conditions and that Strouhal laws are not applicable to purely acoustic instabilities (like screech, for example). In some cases, hydrodynamic instabilities in flames can also interact with lower frequency acoustic modes and give rise to a special nonlinear coupling (Poinsot et al. 1987).. An extended shear layer stability analysis taking into account the effect of acoustic waves has been proposed by Flandro (1986) to predict the "lock in" effects of shear layer instability and acoustic waves in solid rocket motors. Nonlinear effects due to merging vortices are not included in this model and a direct simulation of vortices propagating and coalescing in a flame region appears today as the best prediction tool for these phenomena. Such models are formally similar to the simulation of the axisymmetric jet of Grinstein et al (1987) but should include combustion effects (Kailasanath et al 1985).

I 3. Intrinsic instabilities

Intrinsic instabilities are related to chemistry and thermo-diffusive mechanisms. Their characteristic lengths are of the some order as the flame front thickness. They are directly influenced by the reactants involved. One classical example of intrinsic instability of a flame front is the thermodiffusive instability of plane laminar flames (see the review papers of Sivashinsky 1983, Clavin 1984). In this simple case, stability is conditioned by the ratio of thermal diffusivity to molecular diffusivity (Lewis number). For Lewis numbers larger than unity, the flame front is regular while it becomes cellular for Lewis number smaller than unity (Fig. I 5).
Premixed laminar flames also exhibit intrinsic hydrodynamic instabilities as shown independently by Darrieus (1938) and Landau (1944). Markstein (1951) revised the initial theory of Darrieus and Landau to take into account curvature effects. A modern perspective is given by Clavin (1984). The effect of such instabilities in the case of turbulent flames with high convection velocities is not yet clarified.
Another example of intrinsic instability is obtained in solid propellant rockets. The interaction between the flow field at the propellant surface and the combustion rate is the source of oscillations which can lead to instabilities. Numerous studies have been aimed at the determination of the velocity (or pressure) responses of solid propellants to predict such instabilities.

In the next sections we will examine instability ***experiments involving acoustic interactions***. Classical studies and more recent results are reviewed. The last section describes recent developments in passive and active control of instabilities. ***Active control*** will be emphasized because of its fundamental interest and practical applications.

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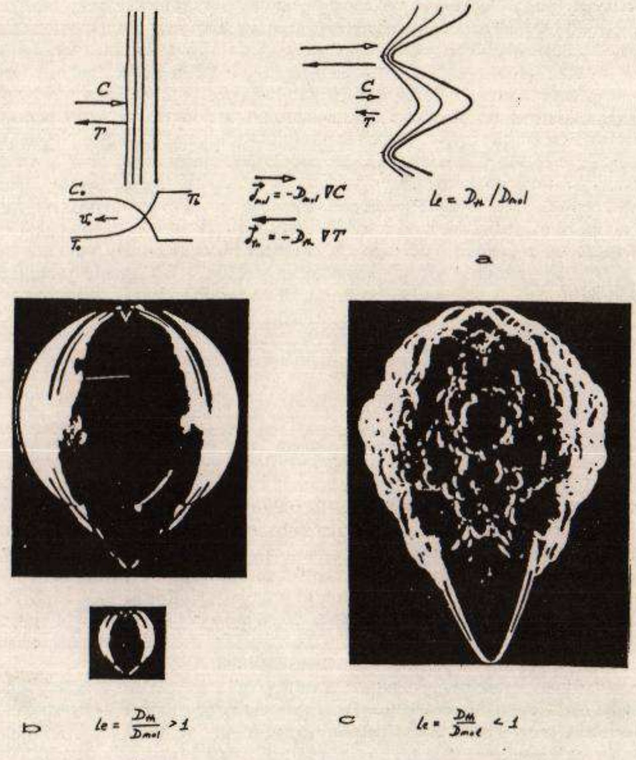

Fig. I 5: Laminar flame instabilities (Sivashinsky 1983)

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II. EXPERIMENTS ON COMBUSTION INSTABILITIES

This chapter summarizes some recent experimental studies of acoustical combustion instabilities. Descriptions of experiments performed before 1970 may be found in Putnam (1971) or Barrère and Williams (1968). The goal of this presentation is to highlight progress made in recent years. In many cases, modern optical diagnostics and data processing have allowed important experimental findings.

This section is subdivided in two parts. ***Non excited (natural) instability modes*** are examined in Section II 1 while ***excited modes*** are considered in Section II 2. Excitation devices are commonly used to study combustion instabilities. These devices are used for example to trigger non-linear instabilities (Barrère et Corbeau 1964, Baum et al 1983) but they have also been employed in many other circumstances to determine transfer functions of flames (Baum et al 1980, Matsui 1981, Narayanaswami et al 1985), measure reflection responses of turbulent ducted flames (Poinsot et al 1986) or excite combustor eigenmodes (Sklyarov and Furletov 1983, Keller et al 1981, Zikikout et al 1986). Results obtained with excitation devices convey information which complements that found in studies of natural modes but the connection between natural and excited modes must be assessed in each specific case. In this paper, corresponding results will be presented separately.

II.1. Natural modes of combustion instabilities

Geometries which have been most frequently considered are summarized in Table II 1.

Table II 1

Geometry	Authors
Backward facing step 	Keller et al 1981 Parker et al 1979 Pitz and Daily 1981,83 Smith and Zukoski 1985 Sterling and Zukoski 1987 Vaneveld et al 1982
Dump combustors, ramjets, singing flames 	Banhawy et al 1978 Clark 1982, 84 Poinsot et al 1986, 87 Yu et al 1987 Lang 1986 Mugridge 1980
Afterburners, V-gutter flames 	Campbell et al 1983 Dowling and Bloxsidge 1984 Yamaguchi et al 1985 Hegde et al 1987 Sivasegram and Whitelaw 1987 Poinsot et al 1987

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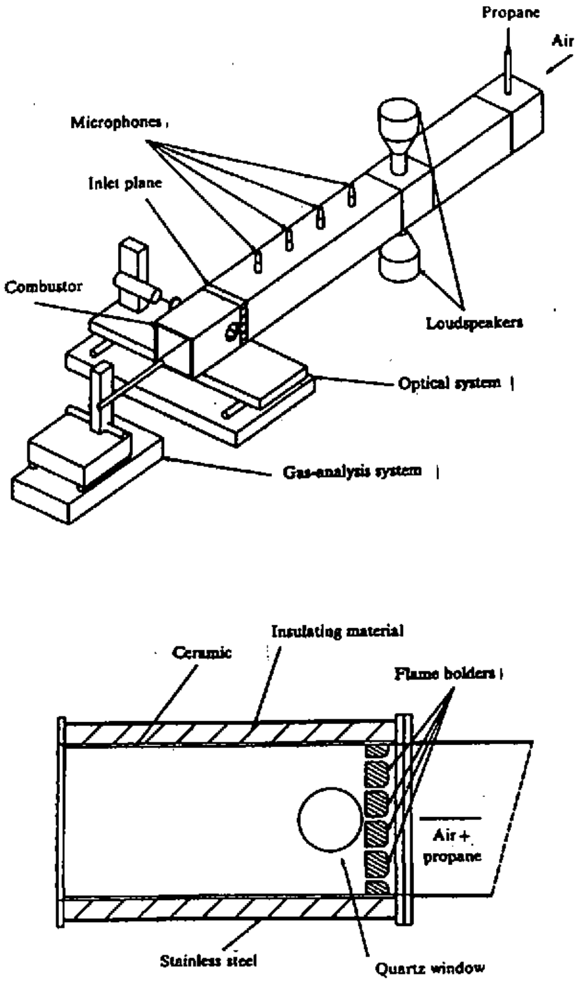

Fig. II 1: Turbulent combustor (Poinsot et al 1987)

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Three main classes may be distinguished: (1) Simple dump combustors such as backward facing step combustors are extensively used because their geometry is close to that found in many practical systems like ramjets but also to fundamental experiments on cold shear layers (2) Dump combustors configurations and more generally geometries where gases are introduced in the combustor through sudden expansion are considered quite often. Singing flames experiments, where combustion is stabilized behind perforated plates also belong to the same configuration type although they are usually laminar (3) Flames stabilized on V-gutters are also of interest because of their application to afterburners.

Results obtained for each of these classes are now examined from a physical point of view. The three classes (1), (2) and (3) exhibit many common features and the analysis will not be done for each of them separately. We will first emphasize the ***importance of acoustics*** in many unstable situations (Section II 1 1). The effect of instabilities on the ***mean flame structure and on the flammability limits*** will be considered in Section II 1 2. Section II 1 3 gives some information on the ***other mechanisms which may couple with acoustic waves and induce instabilities.***

II 1 1. Acoustic interactions

The first feature which clearly appears from studies presented in Table II 1 is the significance of acoustics in instability mechanisms. Most instabilities described in this Table are acoustically controlled and the ***frequency of oscillations may be predicted by simple acoustic calculations of the system eigenmodes.*** It is worth indicating that in most laboratory systems, acoustic eigenmodes are numerous and lead to different coupling effects in the same installation. As an example, consider the dump combustor studied by Darabiha et al (1985) (Fig.II 1). A mixture of air and propane is injected through a long duct into the combustion chamber. The injection plane comprises five narrow injection slots separated by four backward facing steps. Each slot has a rectangular cross section of 3 by 100 mm and the blockage is 85 %. An experimental exploration of the flow regimes of the system is accomplished by varying the air flow rate and the equivalence ratio F (defined as the fuel/air ratio divided by the fuel/air ratio under stoichiometric conditions). The existence of instability is characterized by acoustic monitoring, C2 radical emission detection, Schlieren visualizations and gas analysis. The following results are obtained:

For low values of the equivalence ratio ($F < 0.8$), the combustion regime is smooth and stable, the sound pressure level is low and sound spectral analysis reveal a broadband spectrum with a few discrete peaks. Spark Schlieren photographs show normal turbulent mixing and spreading of the fresh mixture jets (Fig.II 2).

For higher values of the equivalence ratio ($F > 0.8$), the combustion regime becomes unstable, the sound pressure level is increased to 140 - 150 dB in the upstream duct and discrete peaks in the spectrum become predominant. In this situation a preferred mode of oscillation is excited and concentrates most of the acoustic power. The frequency of this mode is not far from the well known quarter wave frequency of the combustion chamber:

$$f\,(\text{Quarter wave}) = C_{sound}/(4\,L) \;=\; 500\ \text{Hz}$$

where C_{sound} is the sound velocity in the combustion chamber and L is its length. However, a more precise investigation of instability and associated flame structure reveals that four different oscillations at 440, 485, 530 and 585 Hz are obtained depending on the operating conditions. For each of these modes, the flame structure itself is different. For example, the 440 Hz mode corresponds to a breathing mode of oscillation of the jets displayed in Fig. II 3 whereas the 530 Hz is associated to the periodic formation of large vortices behind the steps (Fig. II 4). The domains of operating parameters where each of these modes appears, are displayed in Fig. II 5 in an air flow rate - equivalence ratio plane.

Now, it is possible to determine the frequencies of the acoustic eigenmodes of the system in a precise way. In particular, variations of temperature and sections from the air supply to the exhaust system may be taken into account to precisely determine all the longitudinal modes of the system (See Chapter II). Such an analysis was

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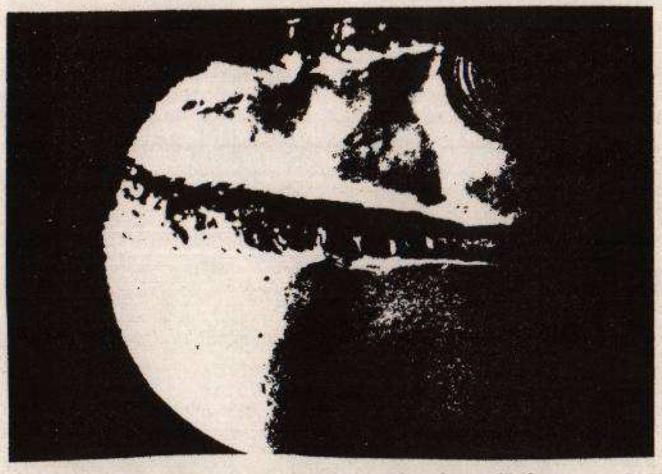

Fig. II 2: Stable combustion (Poinsot et al 1987)

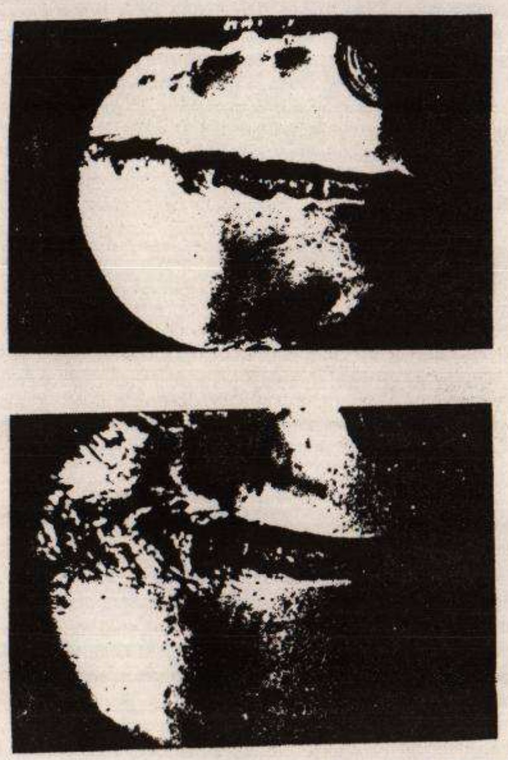

Fig. II 3: Unstable combustion at 440 Hz: breathing mode (Poinsot et al 1987)

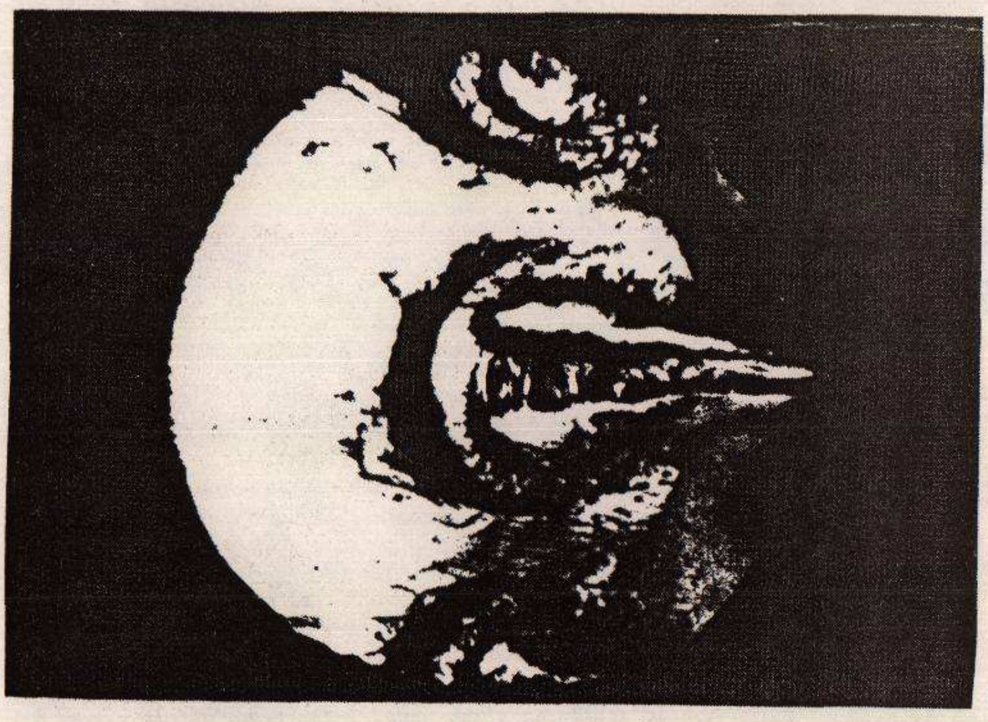

Fig. II 4: Unstable combustion at 530 Hz: vortex mode (Poinsot et al 1987)

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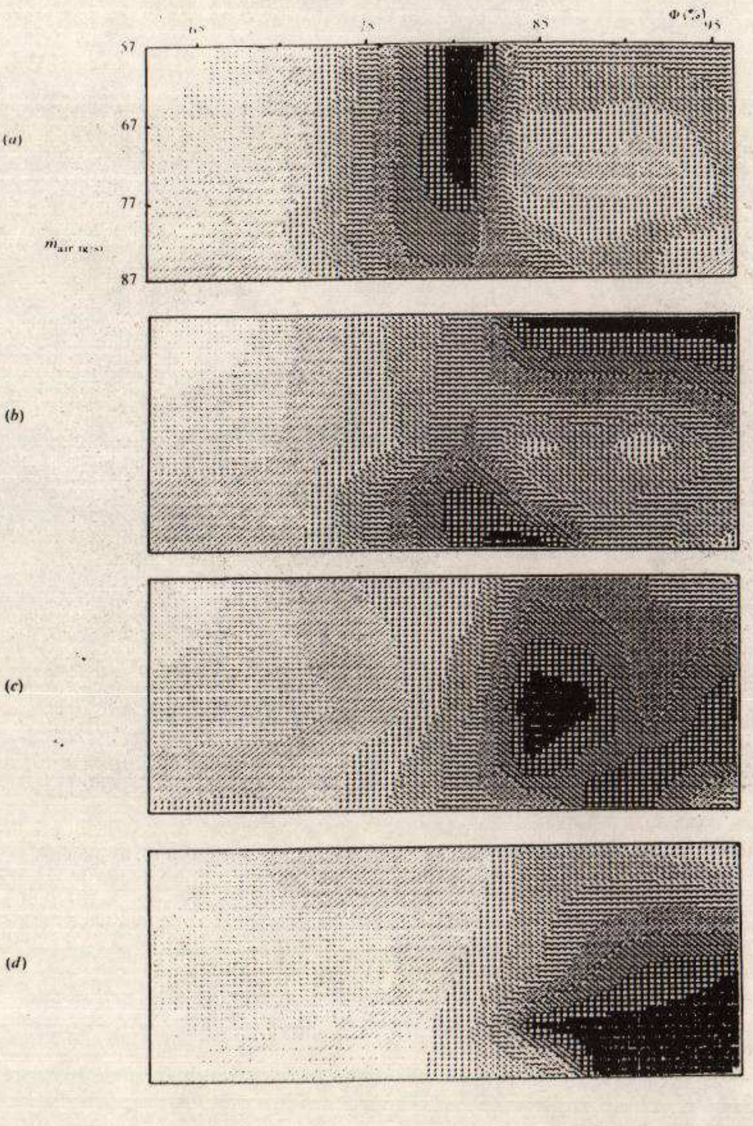

Fig. II 5: Instability domains in a flow rate-equivalence ratio plane (Poinsot et al 1987)

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applied to the combustor of Fig. II 1 and Table II 2 presents the frequencies of these eigenmodes along with the measured frequencies.

Table II 2

Frequencies of acoustic modes (calculated)(Hz)	Frequencies of unstable combustion modes (Hz)
....	
341	350
390	390
440	440
486	485
532	530
586	590
....	

Results show that ***all four modes appearing during unstable combustion (440, 485, 530, 585 Hz) are acoustic eigenmodes of the complete system.*** All these modes are close to the quarter-wave mode of the combustion chamber itself but the nature of the fluid mechanical phenomena associated to these oscillations differ from one mode to the other. The frequency jumps appearing under unstable combustion correspond to transitions from one acoustic mode to the other. These jumps can only be explained by taking into account the complete structure of acoustic waves in the system.

The previous example indicates that the whole system acts on the instability and that these acoustic interactions should be carefully investigated even if one is interested only in chamber instabilities. Furthermore, it indicates that ***predictions of combustion instability frequencies based only on 'quarter wave' estimates*** should be only used as a first guess because they do not take into account the whole system. Results obtained by many authors confirm this point as they show that the choice of the characteristic length imposing the frequency is not clear: this length can be the gas supply channel length, the combustion chamber length or the whole duct length. In the general case, the arbitrary separation of the burner in different parts (from exhaust to flameholder, from flameholder to inlet, etc) can not be justified. The influence of geometrical parameters was carefully examined by Sivasegram and Whitelaw (1987). Changes in the length of the upstream duct modify the flammability and stability limits of confined premixed flames stabilized behind axisymmetric bluff bodies. It is concluded that, in most cases, combustion instability is acoustically controlled and associated to quarter wave frequencies based on the upstream pipe length and their harmonics (a similar result was obtained by Yu et al (1987) in a ramjet experiment.) Extensive parametric studies were performed to determine the effects of upstream contraction and upstream duct length. However, a complete analysis of low frequency acoustic modes was not done.

The same authors also consider oscillations in axisymmetric dump combustors and distinguish two situations:

(1) When the ratio R of the downstream duct to supply duct lengths is larger than 1.5, oscillations are mainly controlled by the downstream duct length (combustion chamber length). However, the oscillation amplitude is even enhanced when a harmonic of the longitudinal frequency of the full length of the combustor is equal to the dominant frequency.

(2) When the ratio R is less than 1.5, the upstream length controls the oscillation frequency and combustion instability is observed only when the acoustic frequency of the full length of the combustor matches the dominant frequency.

Another interesting contribution is due to Mugridge (1980). It concerns combustion driven oscillations in a laminar combustor. Premixed gases are injected through a 65 port inlet into the combustion chamber. Mugridge studies the effect of supply tube and combustion chamber lengths on the instability frequency. It is shown that experimental results do not confirm earlier theoretical calculations based on Merk's model (1956). The length of the combustion chamber appears to be an insufficient parameter to predict the existence of instabilities. This

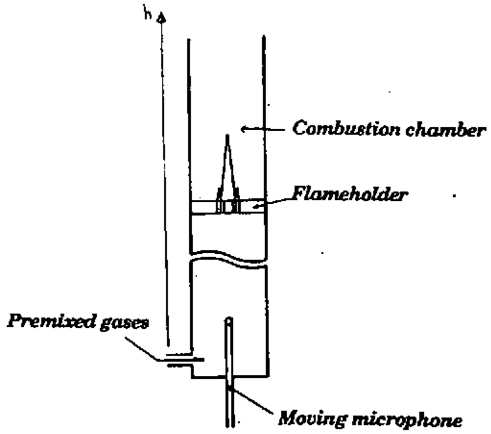

Fig. II 6: Laminar singing flame experiment (Lang 1986)

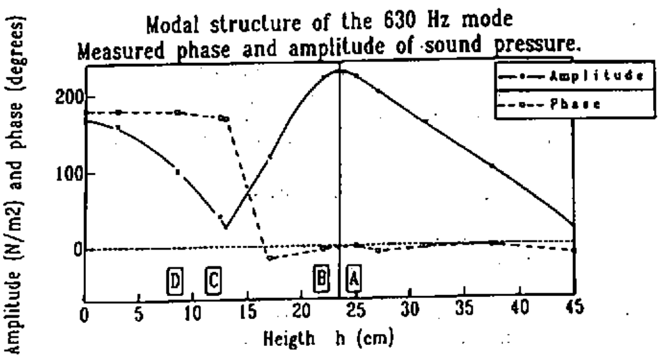

Fig. II 7: Acoustic structure of the 630 Hz mode (Lang et al 1987)

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length remains however an important parameter as shown by Lang (1986) who made experimental studies of a similar burner (Fig. II 6) and showed that for a fixed set of operating conditions, the frequency of instability of his device was a direct function of the combustion chamber length L. This author indicates that this frequency is submitted to jumps when the chamber length is changed and that no instability occurs for small values of L. In all cases, unstable modes have a pressure antinode at the flame holder and a pressure node at the open exit. The effect of supply tube length is not investigated but the acoustic structure measured by the author and displayed in Fig. II 7 reveals that the unstable mode also corresponds to an eigenmode of the complete system with a half wave from system bottom to flameholder and another quarter wave from flameholder to exhaust plane.

These results and many others such as those of Smith and Zukoski (1985) or Raghu and Sreenivasan (1987), Poinsot et al (1987) show that ***a systematic analysis of the longitudinal modes of a given combustor taking into account the complete system from the air supply to the exhaust constitutes a simple and powerful tool to predict the properties of the acoustic eigenmodes of the system and their influence on combustion oscillations .***

All calculated acoustic frequencies of a given system do not appear during combustion. Acoustic eigenmodes impose discrete values of frequencies for which acoustic feedback is possible but the exact range in which coupling may occur is determined by the ***characteristic times of convection and combustion.*** These times are mainly function of the ***fluid mechanical processes taking place in the combustion chamber and cannot be predicted by global models.*** One of the most difficult questions in the prediction of combustion instabilities is the determination of these times. Experimental cases where these times were measured and the associated phenomena were identified, are presented later.

II 1 2. Flammability limits due to instabilities

An important effect of instabilities is to strongly affect the flammability limits of combustors. In many practical systems like ramjets or afterburners, instabilities are the limiting performance factor. They induce vibrations, overheating and thrust variations but they also may lead to extinction through blow-off or flash-back of a single or a group of flames. Results obtained by Sivasegram and Whitelaw (1987) show that rich extinction limits in confined premixed disk stabilized flames are due to low frequency combustion instability. Mugridge (1980) indicates that combustion instabilities in his dump laminar combustor were strong enough to extinguish the flame.

Zikikout et al (1987) consider the effects of combustion instability in a non-premixed turbulent air-propane combustor. The flammability limits and the stability domains are determined as a function of the operating conditions (air flow rate and equivalence ratio). Results displayed in Fig II 8 show that extinction occurs at high values of the air flow rate and extreme values of the equivalence ratio. Fig. II 8 presents two maps of sound spectral amplitude in the low frequency range (f1=360 Hz and f2= 230 Hz) plotted on a grey scale level. The frequencies f1 and f2 are the two dominant low frequency modes appearing in this combustor. Dark regions correspond to high values of the sound intensity and therefore to combustion instability. In both regions where the flame reaches extinction, Fig. II 8 reveals that the ***flame becomes unstable just before extinction.*** The flame is blown off because of low frequency instability. In the case of a low equivalence ratio, extinction is caused by a 230 Hz mode associated to the formation of well defined puffs behind injectors. Rich extinction is due to the 360 Hz oscillation.

Keller et al (1981) investigate the mechanisms leading to flashback in a turbulent backward facing step combustor. The flow pattern is recorded by high speed schlieren cinematography. Many different instability modes are identified: humming, chucking, buzzing. Keller's results may be summarized as follows:

- instabilities are generally due to high values of the equivalence ratio.
- the basic modes leading to combustion instabilities are present at stable operating conditions but their level is low. The same result was obtained by Poinsot (1987) and Zikikout et al (1987) but its interpretation is not straightforward.
- one of the three combustion instability modes could be acoustically excited by loudspeakers. This mode referred to as humming is displayed in Fig. II 9. The corresponding frequency is 160 Hz.
- the two other modes (chucking and buzzing) are due to large flapping motions of the flame front. The frequencies associated with chucking are of the order of 55Hz and the effect of acoustics on chucking could not be asserted.

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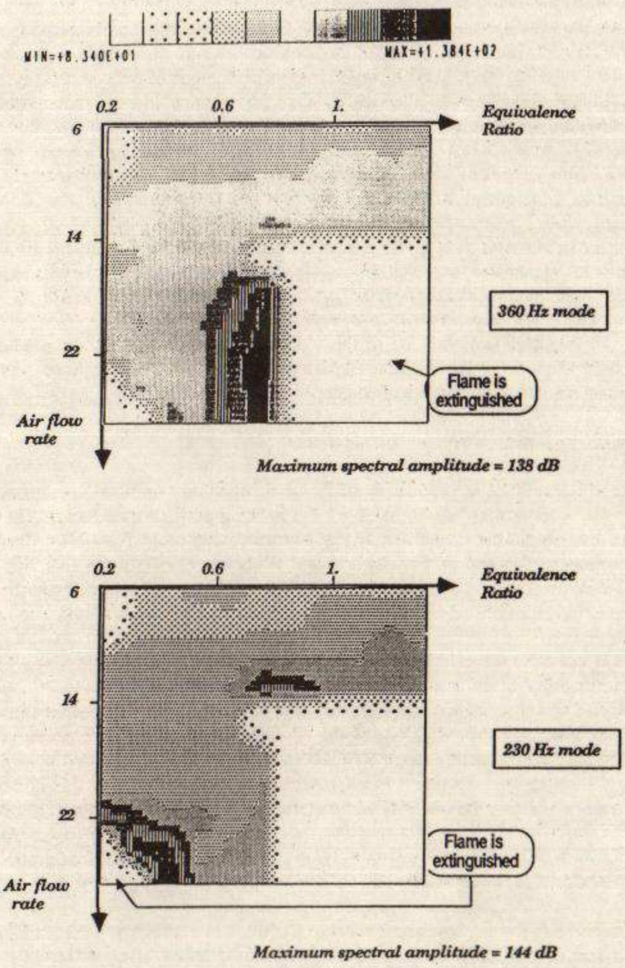
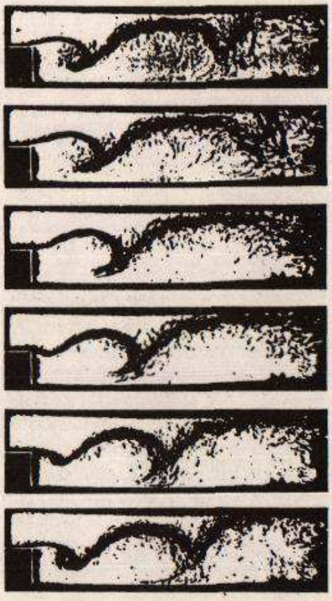
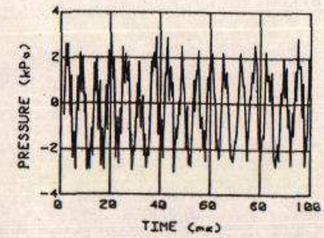


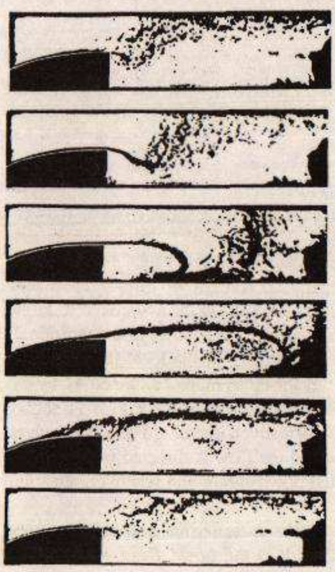
Fig. II 8: Flamability and stability domains in a flow rate-equivalence ratio plane. Diffusion combustor (Zikikout et al 1987)

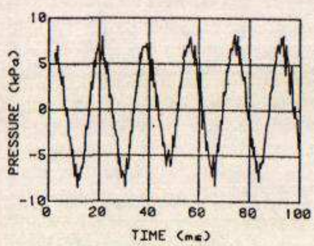




Pressure transducer record of humming

Fig. II 9: Schlieren visualization of humming (Keller et al 1981)





Pressure transducer record of chucking

Fig. II 10: Schlieren visualization of chucking leading to flashback (Keller et al 1981).

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Chucking is the strongest mode (Fig.II 10) and could lead to flame flashback.
These results provide one example of the effect of combustion instabilities on the flammability limits and exhibits one possible mode of interaction. Other examples of the effects of combustion oscillations on the mean flame structure are given in Darabiha et al (1985). These authors present correlations between the amplitude of pressure oscillations and the mean structure of the flow measured by computerized gas analysis. Their results show that the mean flame structure is influenced by combustion instabilities and that a strong correlation could be evidenced between a given mean combustion regime and the corresponding intensity of pressure oscillations for this regime.

II 1 3. What are the mechanisms involved?

In many combustion instabilities, acoustic coupling appears as the first and most evident mechanism. However, if one wishes to understand and predict combustion instabilities, one has to consider the ***other processes involved, mainly the fluid mechanical processes***. Studies based only on correlations between the acoustic characteristics of a given combustor and the existence of instabilities are clearly insufficient. The complete response of the reactive flow must be analyzed. Many studies have been aimed at the detailed study of mechanisms determining transient combustion. Some of this work is theoretical. For example, direct numerical simulations exhibit mechanisms by which flames stabilized by steps respond to external excitation and provide descriptions of flow fields which reproduce features observed in experiments (Jou and Riley 1987, Kailasanath et al 1985, Oran and Boris 1981, Ghoniem et al 1987). While these studies give a wealth of informations, the comparison with experiments is difficult because clear indications on the most important processes (with the exception of acoustics) are usually not available. The situation is made even more complex by the great variety of experimental configurations. It is however instructive to examine the clearest experimental data.

II 1 3 1. Instabilities dominated by essentially acoustic modes

Purely acoustic modes have been identified in different studies. For these modes, instability corresponds to system oscillations where acoustic waves induce large fluctuations of the flow rate entering the combustion chamber. These flow rate perturbations generate combu^stion oscillations which produce feedback effects. No natural hydrodynamic mode is involved. Frequencies are generally low (from 10 to 500 Hz).
Purely acoustic modes are the most common pressure oscillations in systems where acoutic waves can freely propagate upstream and downstream of the combustion chamber. In some circumstances, these modes are even difficult to suppress when one wishes to study other kinds of interaction (Yu et al 1987). Such modes are examined by Smith and Zukoski 1985, Lang 1986, Keller et al 1981, Sterling and Zukoski 1987. Poinsot et al (1987) have made a detailed analysis of an acoustic coupling in the dump combustor of Fig. II 1. In this combustor, the most intense mode of instability, which appears at a frequency of 530 Hz, is associated to large vortices shed behind the steps (Fig. II 4).In this regime, ***pressure signals*** are almost ***sinusoidal*** and conditional measurements are possible. A phase average imaging method was used to obtain maps of the local instantaneous reaction rate at eight different instants of the oscillation cycle. The grid used for these maps contained 41 by 41 points. Spark Schlieren visualizations of the flow field at the same instants were also obtained. Fig. II 11 shows the Schlieren visualization and the phase average maps of reaction rate at the first seven instants. The time interval between each view is 0.23 ms. The inlet plane is at the right of the window and the flow is directed from right to left. These views show how the vortices shed behind the steps are convected downstream and where combustion takes place. The following elements can be deduced from these data:
(1) the phenomenon determining the instant of maximum combustion is ***the interaction between vortices*** issued from neighbouring jets. This occurs at time t6 (Fig. II 11). This result is the ***basic fluid mechanical information*** required to predict combustion instability. The characteristic time of non-steady combustion in this system is the time T needed for a perturbation to travel from the jet lips to the regions where jets interact. As a result, the instability period will be of the order of 2T as shown by Crocco and Cheng (1956). It is worth adding

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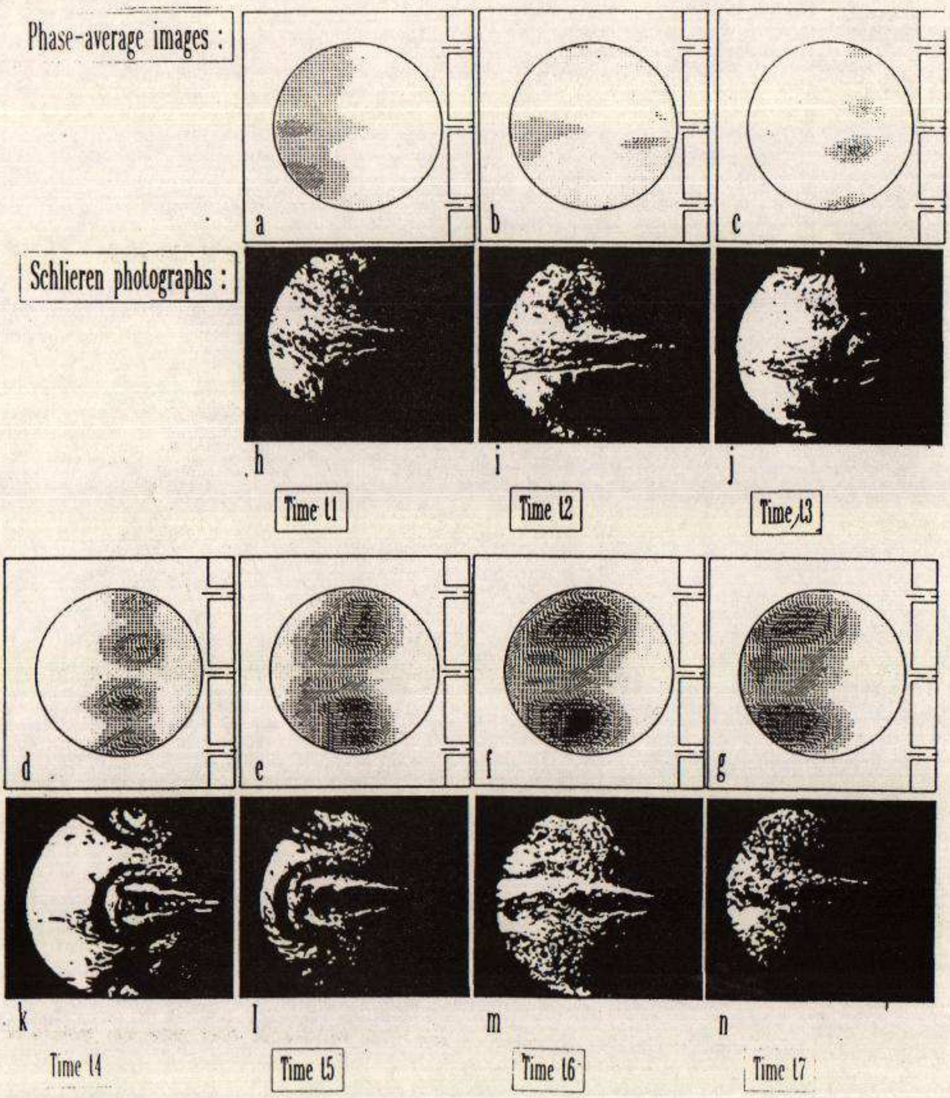

Fig. II 11: Schlieren vizualisation and phase average images of reaction rate for the vortex driven combustion instability (Poinsot et al 1987)

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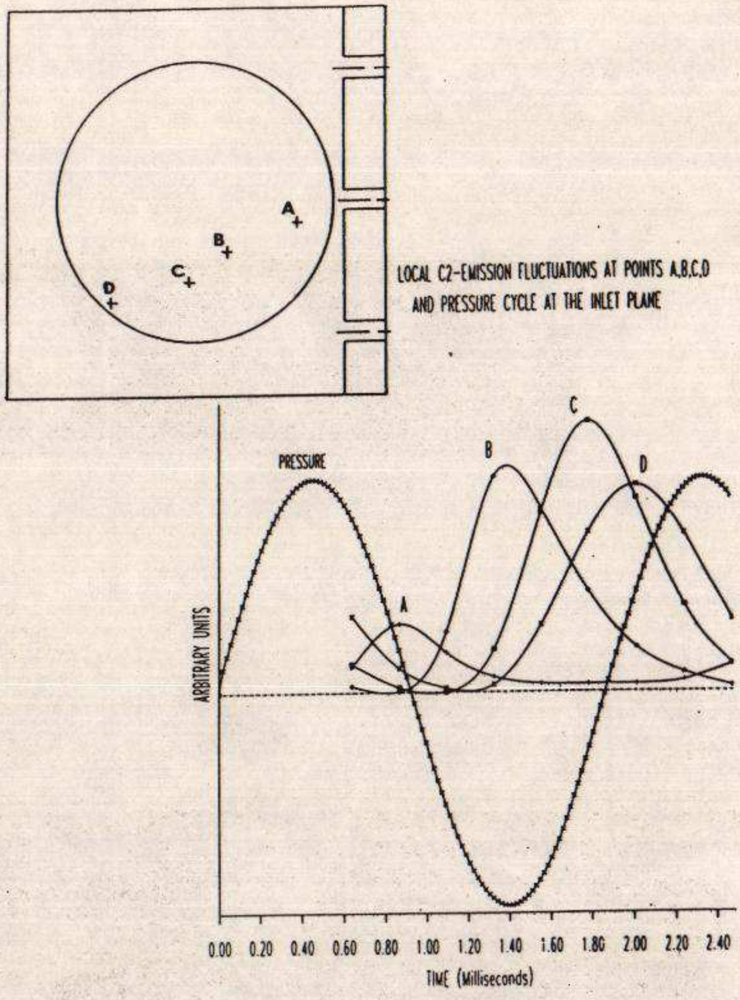

Fig. II 12: Local time variations of pressure and heat release at four different points of the window (Poinsot et al 1987).

that this time is rarely easy to predict. Smith and Zukoski (1985) have studied instability in a backward facing step combustor and they have shown that for this configuration, the fluid mechanical time T corresponds to the time needed for perturbations to be convected from the combustor inlet to the combustor wall. When perturbations reach the wall, strong mixing and combustion take place. This mechanism is somewhat similar to that of interacting vortices in the work of Poinsot et al (1987).

(2) little combustion takes place on the vortex cap. Phase average images show that the reaction rate is maximum in the wake of the vortices. This result suggests that Schlieren pictures should not be used to predict where and when combustion takes place.

(3) a local Rayleigh integral can be evaluated at each measurement point of the grid. Fig. II 12 presents the time variations of pressure and local heat release at four different points A, B, C and D. The pressure fluctuations are assumed to be equal at these points because the wavelength of the acoutic mode is large compared to the reaction zone dimensions. Fig. II 12 shows that the local Rayleigh integral takes negative or positive values. The sign of this quantity depends on the position of the observation point.

POINT	A	B	C	D
Phase between pressure and heat release (°)	90	180	270	290

At point B, the pressure and heat release signals are out of phase and the instability is damped. At point C and D, the instability is strongly amplified. Therefore, the Rayleigh criterion is not verified everywhere in the flow and a simple local measurement cannot be used to check the Rayleigh criterion. Similar results were obtained by Sterling and Zukoski (1987) in their study of ramjet instabilities. These authors showed that points located close to the flameholders were feeding energy into the oscillation whereas downstream points were damping it.

(4) if one considers the global heat release (obtained by integration of the emission signal over the whole grid), a ***global Rayleigh criterion for the complete combustor*** may be determined. Fig. II 13 shows that the phase between this global heat release and the pressure in the combustion chamber is close to 270°. Combustion is maximum when pressure becomes positive. This feature is characteristic of combustion oscillations if the losses of acoustic energy from the combustor are small. It indicates that an ***energy balance*** in the combustor is achieved between zones which feed energy into the oscillation (Points C and D) and regions which extract energy from it (Point B).

(5) finally, vortex shedding is also of interest. Fig. II 14 displays the variations of the inlet velocity fluctuations along with moments t1, t2,.. t7. Fig. II 11 reveals that the vortex is formed at instant t2. This instant corresponds to a maximum positive value of the velocity fluctuations at the inlet. The vortex formation appears as a consequence of a large positive excursion of the jet velocity. The vortex shedding is in the present circumstance only due ***to the large acoustic velocity fluctuations*** induced at the combustor inlet. Hydrodynamic instabilities have no influence on this process (the most amplified frequency of the hydrodynamic modes of the incoming jets is close to 4000 Hz). A similar conclusion is reached by Smith and Zukoski (1985) or Yu et al (1987).

II1 3 2. Hydrodynamic mode contributions.

Many studies concern the possible effects of hydrodynamic instabilities on combustion instabilities. These studies are sometimes inconclusive because hydrodynamic effects are not easily separated from purely acoustic effects. In the case of the vortex driven combustion instability studied by Poinsot et al (1987), hydrodynamic oscillations were shown to have no effect because their preferred frequency (4000 Hz) was far from the frequency of the most unstable mode (530Hz) found in the experiment. Hydrodynamic oscillations induce in this case secondary effects. It is for example possible to distinguish hydrodynamic perturbations growing on the incoming jets (Fig. II 11).

Sivasegram and Whitelaw (1985) studied the *relationship between shedding and acoustic frequencies* in confined disk stabilized flames and concluded that shedding was important only in the small range of equivalence ratios where transition takes place from stable to unstable combustion. Yu et al (1987) consider vortex-exhaust nozzle

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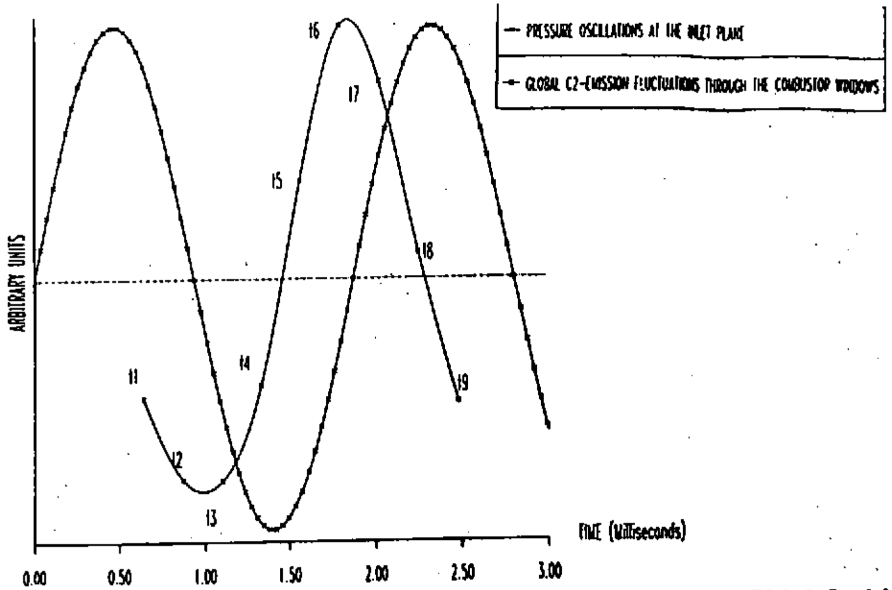

Fig. II 13: Global heat release variations versus pressure variations (Global Rayleigh criterion, Poinsot et al 1987)

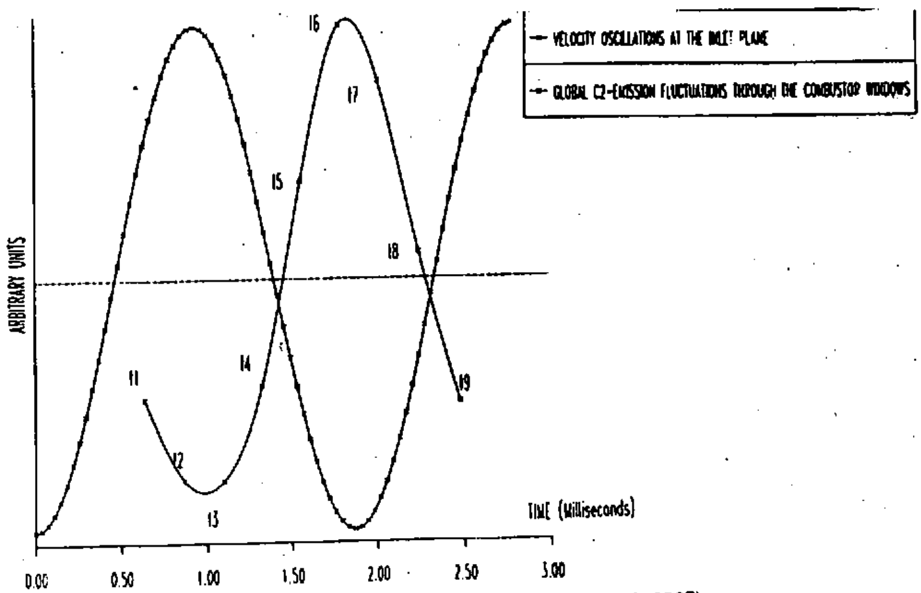

Fig. II 14: Time variations of jet inlet velocity (Poinsot et al 1987).

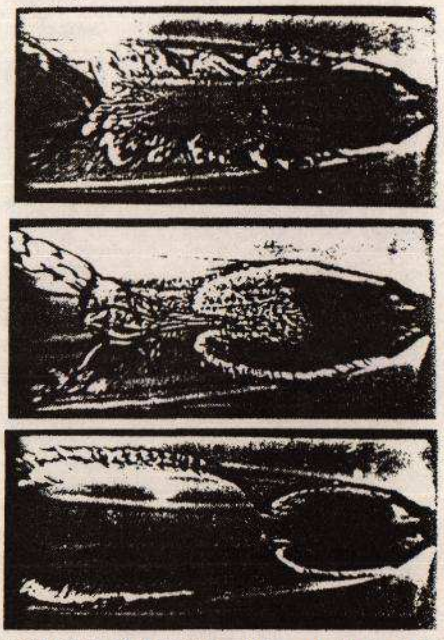

Fig. II 15: Schlieren visualization of buzzing (Campbell et al. 1983)

Fig. II 16: Collective interaction phenomena in a V-gutter stabilized flame. (Poinsot et al 1987).

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interactions to describe ramjet instabilities. Their results reveal no hydrodynamic coupling but only exhibit acoustic effects. The system appears to be controlled by a half wave mode oscillation upstream of the combustion chamber. This purely acoustic mode concentrates the available energy and prevents the development of any other oscillation.

Examples of ***hydrodynamically coupled combustion oscillations*** are found in backward facing steps combustors. Keller et al (1981) describe flapping motions of flames in the absence of acoustic effects. This mode referred to as buzzing is explained by the authors on the basis of both experimental data and of a Random Vortex Simulation as a purely hydrodynamic interaction of the recirculating gases with the flame sheet. While acoustic waves may not be dominant in this case, they are certainly present as indicated by the name chosen for this instability ('buzz'). Fig. II 15 presents Schlieren photographs corresponding to this case.

Poinsot et al (1987) study hydrodynamic modes and collective interactions of vortices in a flame stabilized behind a V-gutter. In their experiment, vortices were shed from the flamehoder lips at a frequency f1 close to the shear layer hydrodynamic frequency (f1=4000 Hz). These vortices are convected downstream, and Schlieren vizualisations show that they coalesce by eight or nine to form a large vortex (Fig. II 16). A spectral imaging method applied to this phenomenon shows that little combustion is taking place in the high frequency hydrodynamic range. Hydrodynamic vortices coalesce before burning. Downstream combustion of the large structures formed by coalescence excite a low frequency acoustic wave of the combustor and induce a flapping motion of the flame sheet at frequency f2=470 Hz. These examples reveal how hydrodynamic and acoustic modes can be nonlinearly coupled and confirms that simple comparisons of hydrodynamic and acoustic frequencies are insufficient in the prediction of combustion instability.

II.2. Excited combustion oscillations

External excitation is used to characterize many features of combustion instabilities. In nonlinear oscillations, excitation devices are a basic experimental element (Barrere and Corbeau 1964, Baum et al 1983). These nonlinear oscillations are encountered mainly in rocket motors. In the case of ramjets or dump combustors, where natural instabilities do not have to be triggered, excitation devices have been used to study some particular features of the combustor response. In this chapter we will only consider ***'positive excitations'*** which are used to excite a particular oscillation mode in a stable combustion regime. ***'Negative' excitations*** (active control for example) which allow the suppression of a given combustion instability by making use of an external control loop will be described in Chapter III.

The effect of acoustic waves on flames has been widely studied (Putnam 1971). Recently, Sklyarov and Furletov (1983) considered the effect of a standing wave on a turbulent flame and showed that acoustic excitation generated vortices and periodic oscillations of heat release thus suggesting possible coupling effects. Matsui (1981) excited a premixed laminar flame with a loudspeaker to measure the transfer function of the flame and compared his results with transfer functions suggested by Merk (1956). He also derived another mathematical model of premixed ducted flame to predict pyro-acoustic amplification by the flame and obtain a new transfer function. A similar study was performed by Lentz (1979). Poinsot et al (1987) used an array of four transducers located upstream of the flame zone to measure the reflection coefficient of a premixed turbulent ducted flame. Their results reveal that the ***reflection coefficient*** of the flame increases with equivalence ratio and ***reaches values beyond unity*** in the transition region between stable and unstable combustion. Furthermore the frequency providing a maximum reflection coefficient corresponds to one of the frequency of instability. The later result suggests that reflection coefficient measurements could be used to characterize the stability margin of combustors. Heckl (1987) also used a four microphone method to identify acoustic waves upstream and downstream of a heating gauze in a Rijke experiment and determine the transfer function of the gauze. This method provides precise and reliable measurements of the transfer functions but it is difficult to apply to flames because of practical considerations. Keller et al (1981) used loudspeaker excitation to increase the amplitude of 'humming' modes in a backward facing step combustor and proved the strong coupling effects between acoutics and combustion oscillations. Zinn and coworkers (1982) developed impedance tube techniques to measure the amplification effects provided by solid propellants during combustion instabilities.

A difficult problem associated with measurements of flame transfer functions is the ***strongly nonlinear***

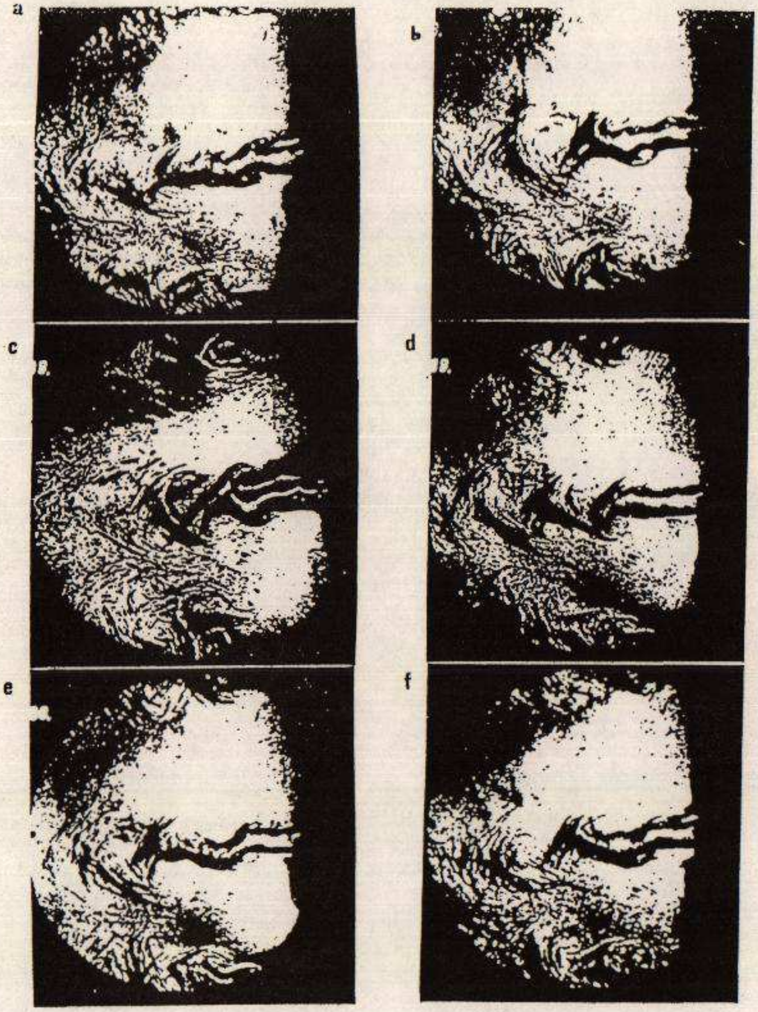

Fig. II 17: Schlieren vizualisation of hydrodynamic vortices generated by acoustic excitation in a turbulent premixed dump combustor (Poinsot et al 1987)

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response of the system in many circumstances. Excitation is an attractive experimental method for high frequency oscillations because it increases their amplitude and makes measurements easier. Now, in turbulent flames, the level of excitation must be high enough to provide satisfactory signal to noise ratio. Under these conditions, nonlinear effects are possible and the determination of a transfer function becomes questionable. Examples of nonlinear coupling between high and low-frequency oscillations may be found in the early studies of Rogers and Marble (1956). These authors indicate that high frequency oscillations in afterburners ('screech') are always coupled to low-frequency oscillations. A recent example of such nonlinear coupling effects is given in Poinsot et al (1987). In this study, the dump combustor shown in Fig II 1 is excited with a set of loudspeakers at a frequency of 3820 Hz. This frequency is close to the hydrodynamic frequency of the jets of fresh gases and the acoutic excitation induces a sinuous motion of the jets (Fig. II 17). The wavelength of vortices displayed on Fig. II 17 corresponds to the frequency of excitation. Now, when the amplitude of the acoustic high frequency excitation is low, the response of the combustor is linear. Fig. II 18 shows that a microphone located upstream of the combustor inlet plane indicates some reduced activity in the low-frequency range but no coupling. If the level of the acoustic excitation is increased beyond a given threshold (Fig. II 19), the high frequency excitation induces a low frequency oscillation at 470 Hz which may be directly related to a flapping motion of the jets superimposed to the vortex shedding occurring on each individual jet. This mode is studied by Poinsot et al (1987) and results show that the response of the system is governed by nonlinear mechanisms of interacting vortices originating from neighbouring jets. This kind of mechanism clearly prevents any measurement of transfer functions and should be considered when such measurements are performed.

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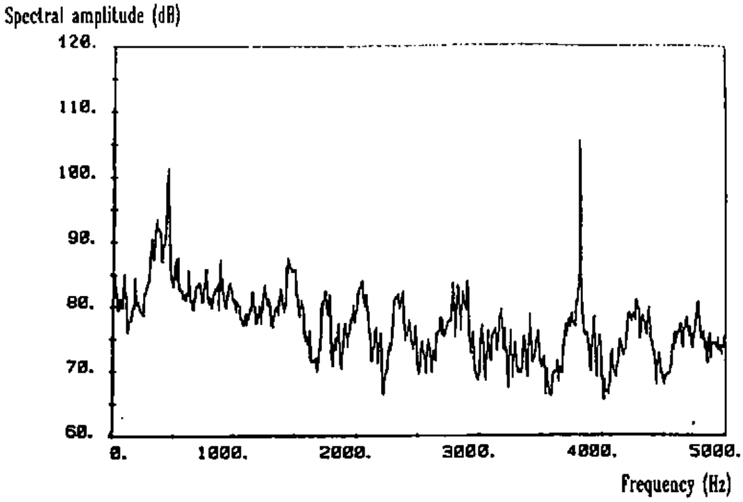

Fig. II 18: Sound spectral analysis of an excited regime with a low acoustic excitation amplitude (Poinsot et al 1987).

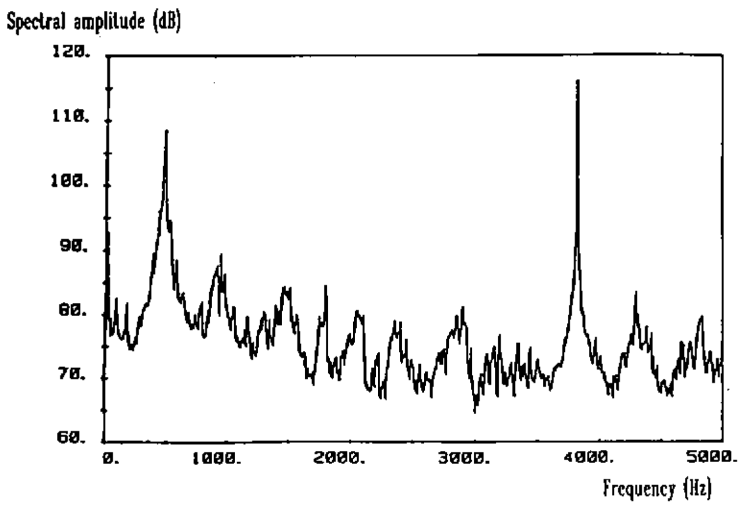

Fig. II 19: Sound spectral analysis of an excited regime with a high acoustic excitation amplitude (Poinsot et al 1987).

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III. CONTROL OF COMBUSTION INSTABILITIES

In many practical situations, a detailed understanding of combustion instability mechanisms is not an engineering objective. Simple and complete suppression of all instabilities is the rule in most combustor development programs (except in certain devices like pulse combustors which are specifically designed to operate in the nonsteady mode). This is achieved in many situations by a process of trial and error which does not include any detailed description of oscillatory phenomena.

From a practical point of view, suppression of combustion instability may be based on:

(1) ***Passive control*** methods which use modifications of geometry, flow conditions, acoustic conditions, addition of specific products in fresh gases etc...

(2) ***Active control*** methods founded on servostabilization techniques. The flame instability is suppressed through a closed feedback loop which return a compensating signalto the system. This method has also been referred to as 'negative excitation'.

Active control methods are more complex than passive methods. Furthermore their practical application to large scale systems is still not demonstrated. These methods are the subject of considerable interests and important developments. Progress in this area will be reviewed in some details because ***active control not only allows combustion instability suppression but also constitutes a powerful method in the study of combustion oscillations.***

III.1 Passive control methods

An extensive description of passive control methods for combustion instabilities is given by Putnam (1971). These classical methods are only briefly described here. Passive devices are based on simple acoustic considerations. The objective is to increase the damping of the acoustic mode which dominates the instability and diminish the possible coupling effects between acoutic waves and non-steady heat release. This can be obtained by quarter wave tubes, acoustic liners, damping and baffles. Typical examples of passive suppression of combustion driven oscillations are given by Sivasegram and Whitelaw (1985) in a study of the combustion oscillations of confined premixed flames stabilized behind bluff bodies. They show that these oscillations may be suppressed by the introduction of a sudden contraction of large area ratio at a proper distance upstream of the flame stabilizer. It is also found that an orifice in the upstream part of the straight feedline was also a possible way of suppressing oscillations. The same authors (1986) also consider instabilities in axisymmetric dump combustors. In that configuration an area constriction of ratio 2 located in the upstream duct about one quarter wavelength from the dump plane could partly suppress the oscillations by diminishing their amplitude by about 10 dB. Quarter-wave tube systems are also used providing a 20 dB sound reduction and the combination of an area constriction with an annular coaxial quarter-wave tube resulted in a 24 dB reduction of the sound level.

Recently, new passive methods have been introduced which do not affect the acoustical combustor properties but the reacting flow properties themselves. The goal of these methods is to design combustion systems which are insensitive to acoustic excitation. Schadow and coworkers (1987) have presented many studies of devices designed to prevent combustion instabilities by decoupling the combustion process from the large scale vortices generated when one of the flow instability frequencies matches one of the system acoustic eigenfrequencies. This frequency mismatch can be achieved in many different ways.

- The first method was tested in an axisymmetric dump combustor. A triangular injector system was used instead of a circular orifice. It was shown that sharp corners in the jet injector introduced locally highly turbulent small scale turbulence without coherent structures. When fuel was injected in these regions, periodic heat release, which is generally caused by combustion in coherent structures, was eliminated and combustion instabilities were avoided.

- The second method was based on shear layer passive control. A nozzle with multiple backward facing steps was used to stabilize a free flame. The multiple backward facing steps system provides velocity profiles with multiple inflection points and therefore generates many non coherent turbulence sources. The stability of this system was tested by acoustical excitation. Planar Laser Induced Fluorescence was used to provide

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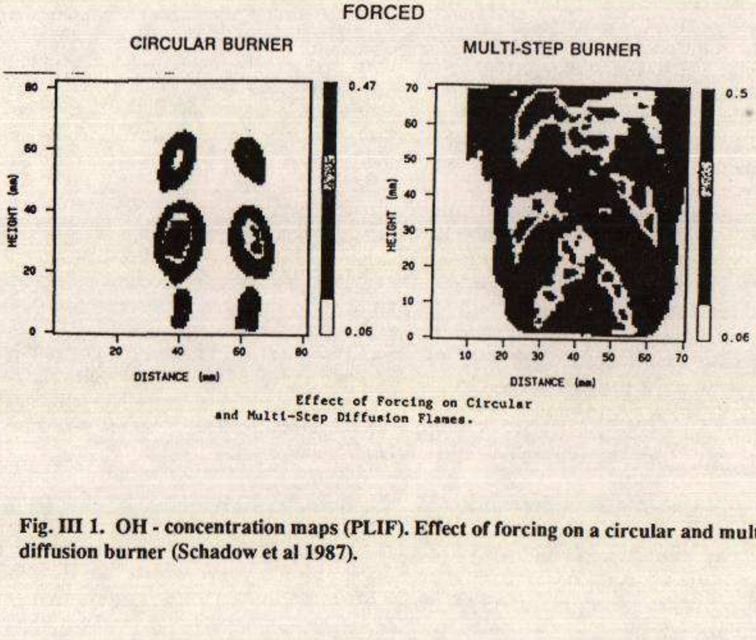

Fig. III 1. OH - concentration maps (PLIF). Effect of forcing on a circular and multi-step diffusion burner (Schadow et al 1987).

concentration maps of the OH radical and detect the formation of reacting structures. Even the highest forcing levels could not generate large scale structures in the multiple step flame. This result was compared with a classical circular burner, which under the same flow and forcing conditions exhibited large scale patterns (Fig. III 1).
In her study of heat sources in acoustic resonators, Heckl (1985) showed that the introduction of a second heat source at an adequate location in an oscillating reacting system could suppress instabilities. She presented experimental and theoretical results obtained in a Rijke tube arrangement. This method has also been used by Raghu and Sreenivasan (1987) to suppress instabilities in a large scale combustor.

III.2 Active control methods

Experimental investigations of combustion instability have often been based on external excitation methods. Mechanical devices like rotating valves, driver units, directed jets, small explosive loads are commonly used to trigger instability modes and analyze their growth or decay (Crocco et al 1960, Culick 1971). External excitation may be used to select specific modes of oscillation, and set a reacting flow in a transverse sloshing motion (Zikikout et al 1986). It is less common to use ***external sources to suppress combustion oscillations***. The idea of active control of combustion oscillations is not new and the work of Tsien (1952), Crocco and Cheng (1956), Marble and Cox (1953) and Marble (1955) contain pertinent calculations of the servostabilization of longitudinal combustion oscillations in rocket engines. At this time these theoretical principles were not verified with experiments.
Recent progress in the related field of anti-sound have suggested that similar methods might be used to control combustion instabilities (Ffowcs Williams 1984, Euromech Colloqium 1986). In the combustion field, studies of Heckl (1985) on a Rijke tube configuration and of Dines (1984), Bloxsidge and Langhorne (1987) or Poinsot et al (1987) indicate that active methods could be used to damp or suppress combustion oscillations.
From a generalized Rayleigh criterion, Chu et al (1988) have shown that ***four theoretical methods could be used for active suppression of combustion instabilities:*** modifications of mass, force, heat release and species source terms. Methods using mass control are based on flow rate periodic modifications to suppress oscillations. Force modifications is achieved for example with oscillating screens which damp acoustic waves in the system. Heat addition control consists of adding energy at points where it discourages the pressure oscillations. Finally species perturbations can also be used to damp oscillations by modulating certain special flow rates (like the fuel flow rate in a non-premixed combustor for example).

Three different examples of active control are now described:

Active control of oscillations in a Rijke tube. Although oscillations in a Rijke tube do not involve combustion, they are very close to many practical combustion instabilities and constitute a good test for control methods. Another advantage of Rijke tube experiments is that the transfer function between flow and heat release is relatively well known which is not the case for reacting flows (Heckl 1985, Raghu and Sreenivasan 1987).
Active instability control of premixed laminar burners. The 'singing flame' experiment is one of the best documented combustion instability and active control was tested in such a configuration by Lang et al (1987).
Active instability control of turbulent combustors. An important question related to active control techniques is the possibility of applying such methods to large scale turbulent combustors. Examples of active control methods applied to medium scale turbulent combustors are considered and the practical implications of these studies for real engines are discussed.

III 2 1. Active control of oscillations in a Rijke tube

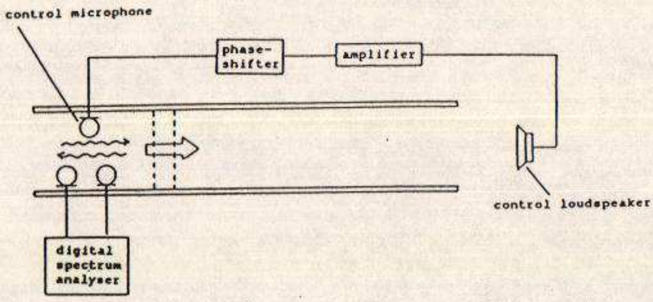

Fig. III 2. Active control of Rijke tube oscillations (Heckl 1985).

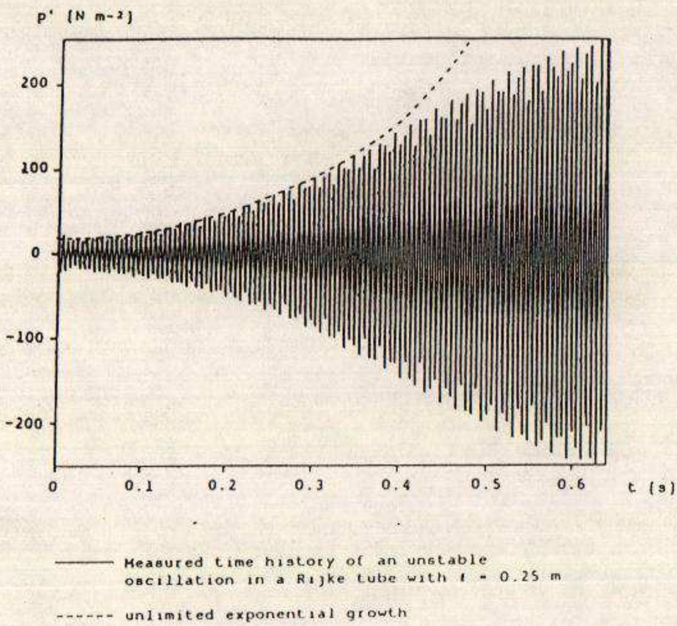

Fig. III 3. Instability initiation studied by active control in a Rijke tube (Heckl 1985).

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In a Rijke tube, a heating gauze placed in a pipe is used to trigger instabilities (Putnam 1971). The oscillations in the Rijke experiment are due to a coupling effect between the non-steady heat release of the gauze and the acoustic waves generated in the tube. Dines (1984) and Heckl (1985) have considered the problem of active control applied to the Rijke experiment and showed that a feedback system using a microphone, a phaseshifter, an amplifier and a loudspeaker were all that was needed to control the oscillations (Fig.III 2). For certain values of the phaseshift, the oscillation amplitude was increased whereas oscillations could be totally suppressed for a wide range of control system parameters. Theoretical predictions of the control system performance based on simple transfer functions of the non-steady heat release were shown to produce satisfactory agreement with experimental results.

As indicated before, active control methods may be used to study many fundamental features of combustion instabilities which could not be characterized by classical techniques. For example, starting from a controlled regime and switching the control system off will produce a natural ***instability onset*** which can be conveniently studied. Heckl used this method to measure the linear amplification rate of the oscillations (Fig.III 3). Another application is to modulate the oscillation amplitude by changing the control system gain and characterize ***non-linear effects***. Heckl applied this technique to control the Rijke tube oscillations amplitude and measure the acoustic loss variations versus the oscillations intensity. These results show that non-linear effects strongly contribute to energy losses at the tube ends when the limit cycle is reached. They also suggest that acoustic impedances conditions cannot be used to accurately predict limit cycle frequencies because the impedance concept is only applicable to linear waves.

Raghu and Sreenivasan (1987) describe passive and active control methods applied to devices resembling the Rijke tubes. Their experimental setup consists of a long pipe in which air is injected through an annular ring located 5cm from the upstream end . Instabilitites are generated by the coupling of the injection shear layer instability with the organ pipe resonant frequencies of the tube. Different control loops were used to assess the theoretical formulation of Chu et al. Closed feedback loops were shown to allow better results at a lower energy expenditure. Active control by forces was successfully tested through fixed or oscillating screens. Heat addition and mass addition methods were also tested and validated.

III 2 2. Active instability control of a premixed laminar burner

The 'singing flame' experiment (Banjawi et al 1978, Putnam 1971, Mugridge 1980) has often been studied because it is the simplest instability example with combustion. Results described in this section are due to Lang et al (1987). This study, a joint effort undertaken by our laboratory with the Technical University of Munich is presented more thoroughly because it provides many general results.

III 2 2 1. Experimental configuration

Experiments were conducted in the premixed propane-air combustor shown in Fig. III 4. The premixing chamber and the combustion chamber are respectively 24 and 21 cm long. The flameholder is a perforated plate with 80 holes of 1.5 mm diameter each. Instrumentation ports along the chamber could be fitted with a microphone or be connected to an acoustic driver unit (loudspeaker) system. Figure III 4 shows four of these ports, named A to D. Since the burner width is 4 cm, only plane acoustic waves propagate at frequencies below 1000 Hz. In this low frequency range, transverse modes are evanescent and a microphone flush mounted on the duct gives the correct value of the sound pressure amplitude in the corresponding section. In this circumstance a side mounted loudspeaker may be used to excite plane wave modes in the duct as the transverse modes generated in this configuration are cut-off and decay exponentially as a function of axial distance. The non-steady heat release is obtained from measurements of OH or C_2 radical light emission.

III 2 2 2. Natural mode of oscillation

All experiments were conducted with an equivalence ratio of 0.8 and a flow rate of 230 ml/sec. In this regime,

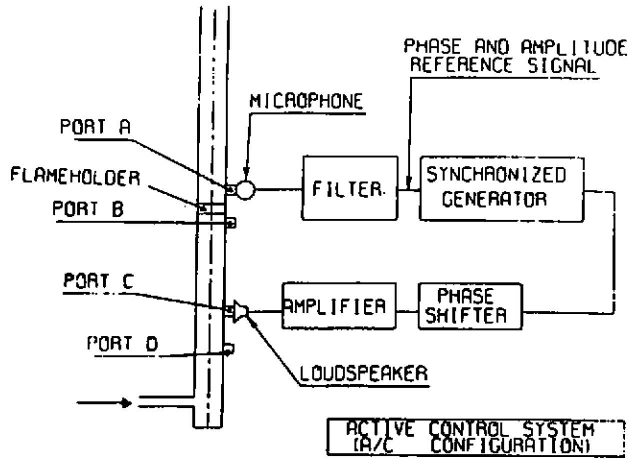

Fig. III 4. Experimental configuration for the premixed laminar burner and Active Instability Control apparatus (Lang et al 1987).

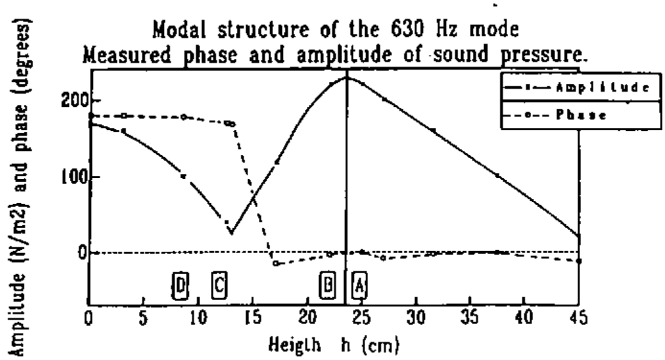

Fig. III 5. Amplitude and phase of sound pressure versus location of the measurement point (Lang et al 1987).

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the system exhibits strong self-sustained vibrations at a frequency of 630 Hz. The maximum sound pressure amplitude measured at port A is 220 Pa. To identify the modal structure, the sound pressure level was measured at different duct heigths of the burner. Fig.III 5 shows the magnitude and phase of the sound pressure versus the location of the measurement point. The microphone signal detected at port A is used as the phase reference. This figure shows that the acoustic oscillation is the second longitudinal mode which may be roughly designated as a three-quarter wave mode. Indeed the bottom of the system acts as a rigid wall while the exhaust may be considered to be a pressure release boundary. Ports A and B are on one side of the pressure node located in the premixing chamber and therefore sound pressure signals at these positions have the same phase. Ports C and D are located on the other side of the pressure node and their phase differs from that of A and B by 180°. This fact will be important in the discussion of stability domains obtained with the AIC system.

III 2 2 3. The active control system

Oscillation control relies on the system shown in Fig. III 4. The sound pressure is measured with a microphone located at one of the ports A,B,C,D. The signal is filtered and used as input to a low-frequency generator. The output of the generator is phase shifted, amplified and sent to a loudspeaker system plugged on the burner. In the low-frequency range considered here, a single loudspeaker is sufficient to excite plane waves in the burner. The amplifier and loudspeaker systems have a maximum power of 10 Watts.
In the first experiment the microphone was placed in the vicinity of the flame at A and the loudspeaker was at C. This configuration will be referred to as an A/C experiment. An important control parameter is the phase shift F introduced by the active noise control system between the microphone signal and the acoustic excitation produced by the loudspeaker. This phase shift is the sum of two terms:

$$F = F_{ps} + F_{el} \quad (1)$$

where F_{ps} is the phase shift introduced by the phase shifter (Fig. III 4) and F_{el} is the phase shift between the output of the phase shifter and the real acoustic signal of the loudspeaker. The phase F_{el} depends on the complete transfer function of the loudspeaker, including its connection to the duct. Separate calibration experiments provide the values of F_{el} corresponding to different frequencies. At 630 Hz this phase is found to be 115°. Equation (1) provides the total phase shift characterizing the control transfer function.
The effect of the AIC system on the sound pressure radiated by the flame (measured at port A) is illustrated in Fig. III 6, which shows the amplitude of the sound pressure plotted with respect to the phase shift. The normal level of oscillation without control is 200 Pa. Measurements were carried out for two values of the gain G:
- For low values of the gain (curve marked by 'x' symbols in Fig. III 6), when F is near 20 °, a reduction of the sound level to 15 Pa is observed. The oscillation is diminished but not suppressed. When F is about 220°, the noise reaches an amplitude of 340 Pa: in this case ***the AIC system acts as an instability amplifier.***
- For a higher value of G, (curve marked by square symbols in Fig. III 6) it is found that a total extinction of noise can be obtained for values of F between -25° and +65°.In this range, the AIC system reduces the noise to a value of 0.1 Pa, which corresponds to ***an attenuation of 1/2000 of the sound level without control.***

This result may be explained in simple terms: the AIC system acts to increase the pressure when the microphone detects a negative fluctuation of the sound level in the system. If the microphone and the loudspeaker are located on different sides of a pressure node, this means that the AIC system should introduce a 0° phase shift between the pressure signal and the acoustic excitation. Experimentally, the values of F providing noise control are indeed close to 0° and cover a wide range of about 90°. A more complete description of the influence of the phase shift and gain is given below.

III 2 2 4. Other control configurations

The effects of phase shift F, gain G, microphone and loudspeaker locations are now investigated to determine the optimal configuration of the AIC system. The microphone and loudspeaker locations are changed and for each configuration the regions of stability in the phase - gain plane (F - G plane) are determined. The experiment already described with the microphone at port A and the loudspeaker at port C yields a stability domain which is about 90° wide and covers more than a factor of 10 in gain (curve A/C in Fig.III 8). The gain

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is given in mV/Pa and corresponds to the electrical voltage at the loudspeaker divided by the sound pressure level measured by the microphone.

If the loudspeaker position is changed to port D, stability may be obtained with a much smaller gain than in the first case while the phase remains in the same range (curve A/D in Fig. III 7). This corresponds to the fact that ports C and D are on the same side of the pressure node but closer to the pressure antinode (Fig.III 5). As a consequence this configuration provides a better coupling between the loudspeaker and the standing wave.

When the loudspeaker is at port B (curve A/B in Fig.III 7), the loudspeaker and the microphone are on the same side of the pressure node (Fig. III 5). Wave damping is then expected for a phase shift range centered in the neighborhood of 180°. Since the standing wave pressure level is even larger than at port D, stability is achieved with a smaller gain.

The last measurement corresponds to the loudspeaker and microphone placed at the same level D and attached to opposite sides of the burner (curve D/D in Fig. III 7). In this situation extinction is obtained when F is about 180°, but it also requires higher values of the gain, because the microphone detects smaller pressure oscillations.

The stability domains are about 90° wide. The measurements indicate that the centers of these regions are shifted with respect to 0° or 180° to about 30° and 210°. This difference from the expected value may be due to several reasons. First, an uncertainty of 20° must be taken into account in the measurement of the phase difference F_{el} between the electrical input of the loudspeaker and its pressure signal. Second, the standing wave description adopted above may be too simple. A more complex transfer function may be required to model the propagation in the system (Roure 1985). Nevertheless the measured phase shift values are close to 0° and 180° and essentially confirm the present interpretation.

III 2 2 5. Transient behaviour and energy consumption of the AIC system

One of the most important questions about AIC is the amount of energy needed to control a specific combustion system. In the present experiment, when the oscillation is actively controlled, the power needed by the loudspeaker is almost negligible (less than 1 mW). This reveals an important difference between active instability control and other active noise control systems. In classical active noise control systems, silence is obtained by superposing the sound pressure wave and the control system pressure signal (see for example Ffowcs Williams (1984) and Burgess (1981)). The noise source is not changed by the control system. In the case of flame instability, the AIC system suppresses the oscillation by directly controlling the sound emission of the flame. Furthermore, the AIC system not only suppresses the noise radiated by the flame, it also stops the coupled flame front oscillations as can be verified by a simple direct observation of the flame. This explains why the energy needed at equilibrium for continuous stability control by the system is small. In practical applications the system must also be able to suppress an instability by starting with the highest possible oscillation. In this case, a maximum amount of energy would be needed during the first instants of active control before reaching equilibrium.

To measure this maximum energy input the control system was stopped. When the natural oscillation was fully established with a sound pressure level of 200 Pa at the flame, the control loop was switched on. The experiment was carried out in the A/B configuration. In Fig. III 7 the set of parameters used for the AIC system is marked by a cross symbol. The pressure signal P and the electrical input of the loudspeaker during this experiment are displayed in Fig. III 8. This figure also shows the fluctuations of the global heat release Q in the burner deduced from OH radical light emission measurements. After the control system is activated, the instability is suppressed in less than 80 ms and the maximum electrical power used by the loudspeaker is 16 mW only. The fact that in a laboratory burner the suppression of oscillation is possible with such a small electrical power suggests that the idea may be applicable to larger scale systems as well.

A last example of the AIC system possibilities is given in Fig.III 9. In this experiment, the flame instabilities are initially controlled by the AIC system and the system is switched-off at time t=0. In this situation the instability grows and Fig.III 9 displays the variations of pressure P and heat release Q during instability initiation. Important information may be extracted from this experiment:

-the linear stability gain can be easily measured during the first cycles of the oscillation growth. This quantity is of

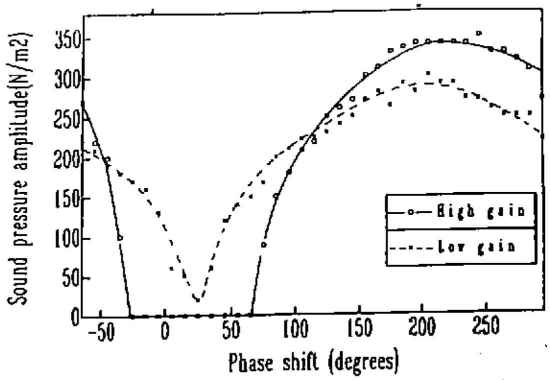

Fig. III 6. Sound pressure measured at port A versus phase shift of the AIC system (Lang et al 1987).

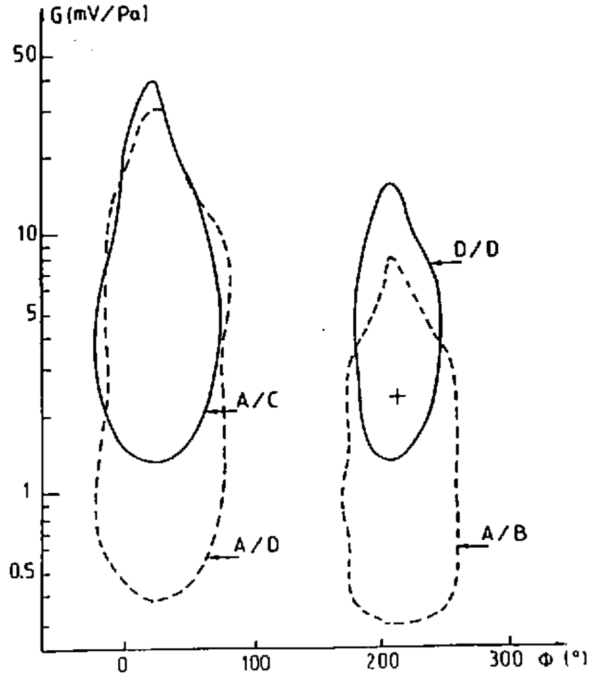

Fig. III 7. Stability domains in the phase - gain plane of the AIC system for different configurations (Lang et al 1987).

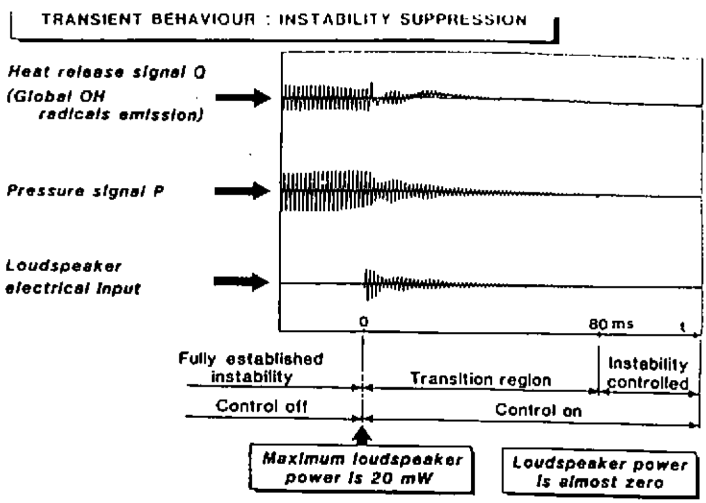

Fig. III 8. Transient behaviour of oscillations: instability suppression (Lang et al 1987).

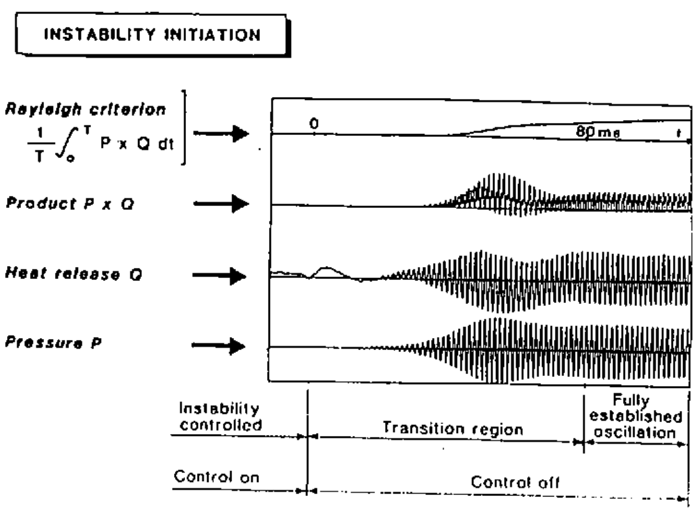

Fig. III 9. Transient behaviour of oscillations: instability initiation (Lang et al 1987).

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importance because it is an output of linear stability models (Tsien 1952, Crocco and Cheng 1956) and can be directly compared to theoretical results.

- Fig. III 9 also displays the function PxQ which determines the Rayleigh criterion for amplification. The variation of this function conveys interesting information on the transition of the initial oscillation to the final limit-cycle. For example, the oscillation amplitude appears to be maximum during the growth of instability and to decay afterwards to its limit cycle value. This is a characteristic feature of nonlinear system oscillations.

III 2 3. Active instability control of turbulent combustors.

The premixed laminar burner shown in Fig.III 4 is not truly representative of practical combustion system which are usually turbulent and develop powers greatly exceeding 1 kW. Furthermore the effect of turbulence on active control system performance has to be considered before applying this method to real engines or burners. Raghu and Sreenivasan(1987) present a mixed active/passive control method of oscillations in a large turbulent combustor by the introduction of two mesh screens at velocity antinodes and four heating coils used to add heat at points where heat addition discourages the pressure oscillations. This combined force and heat addition system allowed a complete elimination of oscillations in the combustion tunnel over a significant range of operating conditions.

Bloxsidge et al (1987) used active control based on flow modulation in an laboratory afterburner channel and reported 20 dB sound attenuation of the so called 'reheat buzz'. The power of their experimental setup was 250 kW. Active control also suppressed the harmonic modes of the fundamental frequency.

A 250 kW non-premixed turbulent combustor was also used at E.M2.C. laboratory to validate active control on large scale systems. This study is now described here in more details (see also Poinsot et al 1987, 1988).

III 2 3 1. Experimental configuration

The 250 kW turbulent combustor is squetched in figure III 10. This combustor is 30 cm long and has a rectangular 10 x 5 cm^2 cross section. The chamber lateral walls are quartz windows which allow flame visualization and optical measurements. The chamber is connected upstream to a long duct of the same cross section. This duct is fitted with instrumentation plugs. Upstream and downstream ends of the combustor are acoustically open. Air is supplied to the combustor at the upstream end of the duct. Propane is injected in the air flow through six narrow slots. The slots are in recess with respect to three backward facing steps.

III 2 3 2. Description of an unstable regime

The experiments were performed with an air flow rate of 24 g/s and an equivalence ratio of 0.4. For this regime, the combustor exhibits a strong instability corresponding to a longitudinal acoustic mode of the combustion device at a frequency of 230Hz. In this experiment, heat release was obtained from C_2 or OH light emission detection. Both radicals provided equivalent results. Spectral analysis of pressure and heat release reveal strong peaks at 230 Hz (Fig. III 11 and III 12). This instability is characterized by a particularly high acoustic level (1700 Pa) and large movements of the flame front. A Schlieren picture of the flames indicates that the mean structure of the jets is modulated by the acoustic oscillation (Fig. III 13). In addition to the turbulence of the flow, ***large scale structures*** ("puffs") appear as characteristic patterns of the ***unstable reacting flow*** and are convected downstream. These structures are formed at the acoustic mode frequency (230 Hz). This instability mode is the result of the interaction between a resonant duct mode and the non steady heat release of the flame.

III 2 3 3. Instability control

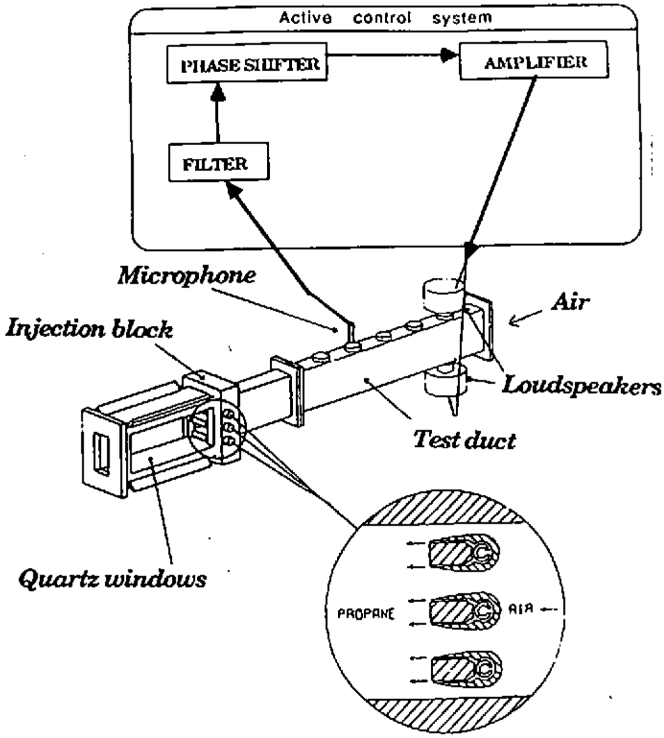

Fig. III 10. Schematic diagram of the 250 kW turbulent combustor (Poinsot et al 1987)

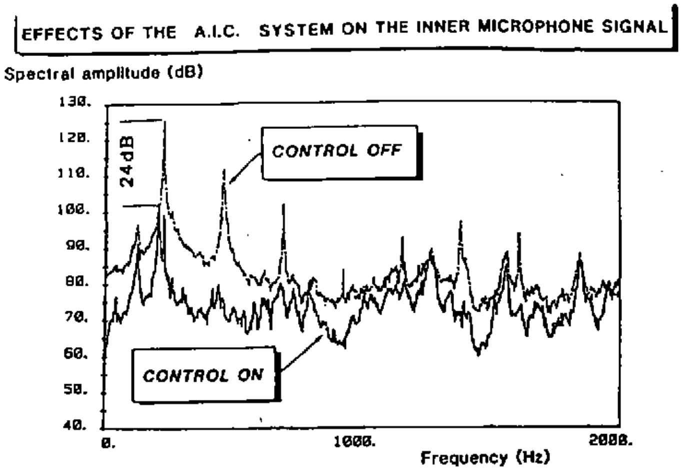

Fig. III 11. Spectral content of the microphone signal with and without control (Poinsot et al 1987).

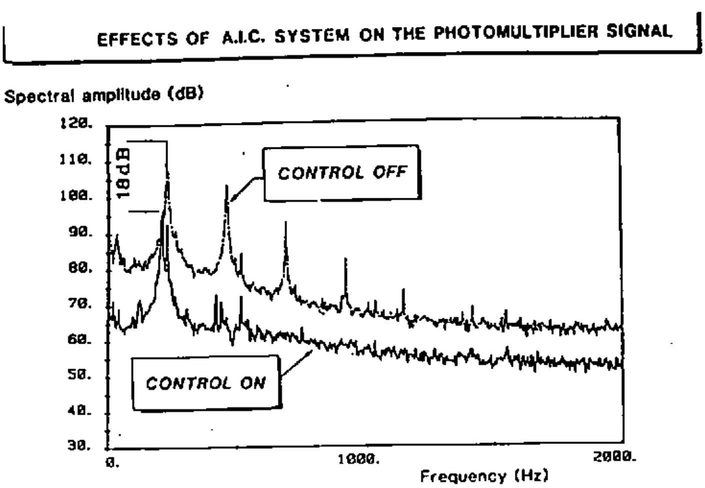

Fig. III 12. Spectral content of the photomultiplier signal with and without control (Poinsot et al 1987).

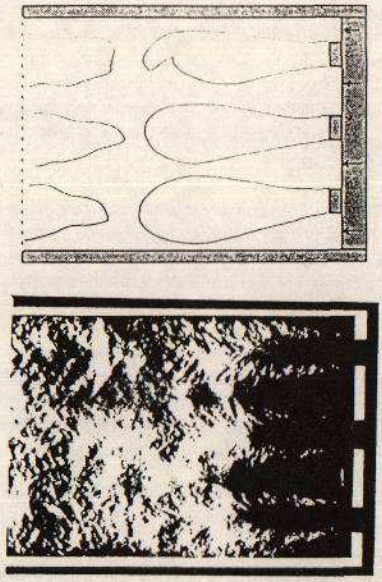

Fig. III 13. Schlieren picture of the flames without control (Poinsot et al 1987).

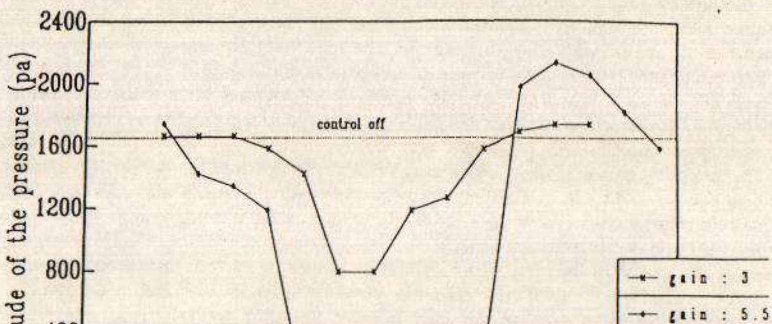

Fig. III 14. Amplitude of the acoustic pressure amplitude versus total delay (Poinsot et al 1987).

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The oscillation is suppressed with a simple feeedback loop. A microphone located on the test duct detects the acoustic pressure upstream of the chamber. The microphone signal is then filtered, phase-shifted with an analog "bucket-brigade" delay line, amplified and sent to a pair of loudspeakers. These loudspeakers are plugged on the test duct, one facing the other at 20 cm from the microphone. A low-pass filter with a cut-off frequency of 3 kHz is used to suppress Larsen effects.

The offset introduced by the delay line is 2.1 ms. Moreover, for the frequency of 230 Hz, the different components of the control device (microphone, filter, amplifier, and loudspeaker) introduce a delay of 1.35 ms. The total delay of the control device is then :

$T_{tot} = 3.45 + T_{dl}$ (ms)

Figure III 14 represents the amplitude of the acoustic pressure with respect to the delay introduced by the control loop. For a sufficiently high amplifier gain, and for delays between 4.7 and 6.4 ms the pressure level is reduced to 120 Pa. When the delay is greater than 6.4 ms, the acoustic level exceeds the sound pressure level without control. The AIC system then acts as an excitation device and enhances the instability. In this case, the combustion region is strongly pulsated, and extinction of one of the injectors may occur. For delays in the range (4.7 , 6.4) ms, spectral analysis of the pressure signal reveals ***an attenuation of 24 dB*** of the peak at 230 Hz, with a ***complete suppression of the harmonics*** (Fig. III 11). The residual noise is principally due to the flow turbulence. At the same time, the peak at 230 Hz in the heat-release signal is reduced by 22 dB (Fig. III 12) and a Schlieren picture of the flames with control shows a standard pattern of turbulent burning jets without puffs (Fig. III 15). The flame structure with AIC appears to be similar to that of a stable combustion region. It is also worth noting that ***AIC greatly increases the stability and operating domains of the combustor.***

The time delay of the control system providing noise suppression can not be related in the present case to simple phase shift as in the laminar burner experiment. A study of the acoustic structure of the oscillation without control shows that this mode is a complex combination of standing and travelling waves. Therefore, the time delay leading to noise suppression depends on the relative distance between microphone and loudspeakers and do not take simple values as in the case of a standing mode of oscillation.

III 2 3 4. Initiation of turbulent combustion instabilities.

The AIC system can also be used to ***trigger and study combustion instability initiation***. Figure III 16 displays the time recordings of pressure oscillation P and heat release signal Q during instability growth. Before time t=0, instability is controlled with a gain of 4 and a delay of 5.2 ms. At time t=0, the AIC system is switched off and ***instability begins to grow***. The following phenomena are observed:

- Between t=0 and t=0.2 s, many frequencies appear on both signals. This effect was not observed in the laminar burner experiment. It is both due to turbulent fluctuations and secondary acoustic modes which are not affected by the AIC device (as for example the 130 Hz peak in Fig.III 11). This phenomenon exhibits one limit of the present system which only supresses the main acoustic mode.
- The instability growth is slow, which means that the linear instability gain is only slightly greater than one. About one hundred cycles (t=0.4s) are needed to obtain a fully established oscillation. This is a characteristic feature of some turbulent combustion instabilities which exhibit metastable and hysteresis behavior.
- A limit cycle is obtained after time t=0.4s. This time corresponds to a vanishing value of the heat release signal. The growth of the oscillation amplitude is limited by the fact that the total heat release must remain positive. Therefore, the ***limit cycle*** amplitude obtained in Fig.III 16 is mainly determined by the ***saturation of combustion rate oscillations and not by acoustic losses.***

Further results on combustion instability initiation can be found in Poinsot et al (1988).

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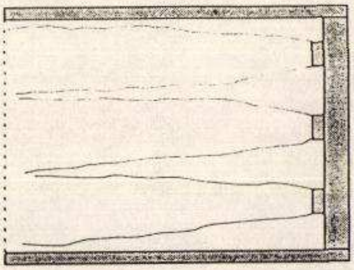

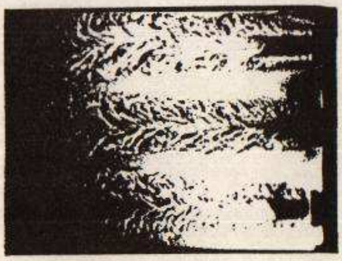

Fig. III 15. Schlieren picture of the flames with control (Poinsot et al 1987).

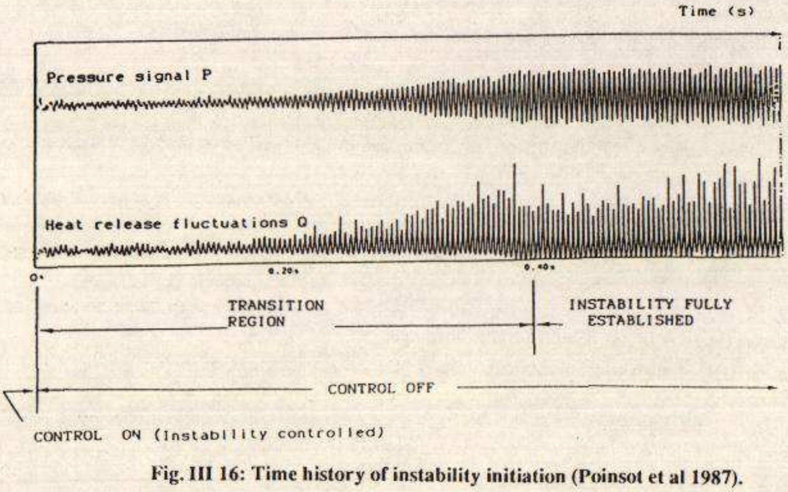

Fig. III 16: Time history of instability initiation (Poinsot et al 1987).

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