# Interaction of Bluff Body Flames with the Shear Layer under Harmonic Excitation

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# **1** Introduction

This paper considers the dynamics of acoustically forced, bluff body flames. Its objective is to determine the key factors that influence the flame's heat release response to excitation. Understanding this problem requires understanding of the characteristics of the velocity field that is perturbing the flame, as well as the response of the flame to this oscillating velocity field. This flame response is controlled by kinematic restoration processes [1], wherein the flame propagates into the flow field at the local flame speed and acts to smooth out the perturbations on the front [2].



Figure 1: Various pathways for acoustic waves to interact with the flame and flowfield

The flow is a complex interaction of a boundary layer, free shear layer and wake [3]. In turn, each of these constituent flow-fields exhibits a range of dynamics [4]. Both absolute and convective instabilities are present – asymmetric vortex shedding, due to the wake, and Kelvin-Helmholtz instability, due to the separated shear layer, respectively. The wake mode, which is responsible for the von Karman vortex street in the non-reacting case, has a frequency which scales as  $f_k \sim U_o/D$ . The most amplified frequency of shear layer oscillations,  $f_{SL}$ , scales as  $U_s/\theta$ , where  $\theta$  is the shear layer thickness and  $U_s$  is the velocity at the point of rollup of the shear layer. At high Reynolds numbers where the shear layer thickness is small relative to the bluff body size, the frequency of the most amplified shear layer mode is much higher than that of the absolute instability of the wake.

As noted above, understanding of the acoustically forced, reacting flow problem requires understanding of the characteristics of the velocity field that is actually perturbing the flame. The incident acoustic oscillation is accompanied by flow oscillations that, in principle, disturb the flame. These perturbations influence both the shear layer and wake that, in principle, can result in hydrodynamic fluctuations associated with these instabilities. As such, the overall flame response is potentially controlled by the superposition of three flow disturbances, as illustrated in Figure 1. However, we will argue in this paper that the most important flow disturbance that wrinkles the flame arises from the unstable shear layer. In other words, acoustic flow excitation disturbs the shear layer, which rolls up into intense regions of fluctuating vorticity that are phase locked to that of the excitation. This result is consistent with recent work showing that unforced, higher density ratio flame dynamics are controlled by the shear layer, as the wake mode instability is suppressed at density ratios  $\rho_{tt}/\rho_b$ >2 [5]. It is possible that the wake mode could similarly control the forced response of the flame in low density ratio flames, or in flames near blowoff [6]. However, these are not the conditions of interest for this paper. The objective of this paper is to further elucidate the physical processes that control the velocity fluctuations disturbing high density ratio, well stabilized flames.

#### **2** Experimental Facility

Experiments were carried out in an atmospheric pressure burner with a square cross-section (3.75" x 3.75") that is 3' long (Figure 2). Natural gas and air are introduced in a mixing chamber located at the base of the burner. The fuel and air flow rates are measured with rotameters with accuracies of 4%. The mixture exits the mixing chamber into a six inch long tube of the same cross-section as the burner, which also contains two 100 W Walsch PA acoustic loudspeakers. The mixture then passes through a honeycomb grid flow straightening section, beyond which it flows all the way up to the exit of the channel. The cylindrical bluff body is mounted at the immediate exit of the channel. Experiments were done at flow rates between 800 lpm and 2200 lpm. The corresponding Reynolds numbers are  $1000 < Re_D < 2400$ , where  $Re_D$  is based on the bluff body diameter and the centerline velocity. The turbulent intensities in the approach flow were about 6%. Analysis of the flame dynamics were carried out using data from Mie scattering experiments. The vorticity fields were computed by measuring the velocity field using Particle-Image-Velocimetry (PIV). These diagnostics are described in Refs.[7,8].



Figure 2: (Left) Schematic of the experimental facility, drawn to scale. Dimensions are in inches. (Right) Coordinate system and reference axes used for quantifying flame position.

## **3** Results and Discussion

In the absence of acoustic forcing, there are no *periodic* disturbances of the flame front, although it does exhibit occasional, apparently random corrugation, as also discussed by Mehta & Soteriou [9]. As acoustic forcing is introduced, periodic distortions of the flame front, due to the roll-up of the separated shear layer into coherent structures, are evident in the flames. The flame is vulnerable to shear layer excitation, as an appreciable fraction of it lies within that region (at least in cases with high flow velocity relative to the flame speed) - this is true especially at the base, where the shear layer is strongest. This can be seen from Figure 3 which plots the time averaged vorticity distribution, as well as the instantaneous flame location for a number of realizations.



Figure 3: (Left) Vorticity contours (colored regions) and flame brush (thin black lines). Mean velocity:  $U_o = 1.8$  m/s, equivalence ratio:  $\phi = 0.8$ , amplitude of excitation:  $u'/U_o=0$ . The thick black lines denote the mean flame position. A sketch of a bluff body is also shown for reference The dimensions on the scale are in meters. (Right) Instantaneous snapshot of the flame motion.  $St_D = f_o D/U_o = 0.80$ ,  $u'/U_o = 0.01$ . The gray region denotes seeded reactants and the black region products.

An instantaneous realization of the flame during excitation is shown in Figure 3 (right). The roll up of the flame by vortical flow structures is evident near the flame base. Farther downstream, flame propagation normal to itself smoothes these wrinkles out. The period of formation of these structures is exactly commensurate with that of the acoustic excitation,  $f_o$ . These structures apparently originate at the bluff body and propagate in the direction of the mean flow. As expected, the spatial wavelength of these structures is related to the convective wavelength,  $\lambda_c - i.e.$ , the distance that the perturbation convects in one acoustic period,  $\lambda_c = U_o/f_o$ . As such, the wavelength of the flame disturbances shrinks with increases in frequency and/or decreases in velocity.

Figure 4 (left) plots the vorticity field distribution in the x direction at a height of y/D=0.5. The forced results were obtained by ensemble averaging over 128 phase locked PIV images. In the unforced case, the vorticity concentration in the shear layers are evident. In the forced case, this plot clearly shows the modulation of the vorticity field about this average value. As noted above, the flame lies within the shear layer, and thus interacts with these vorticity disturbances. In addition, the flame generates both mean and fluctuating vorticity due to the misaligned pressure and density gradients, the baroclinic mechanism. In a flow with a favorable pressure gradient, this vorticity is of opposite sign as shear generated vorticity. As such, baroclinic generated vorticity gradually diminishes the magnitude of shear generated vorticity with axial distance. In fact, the vorticity magnitude eventually goes to zero far enough downstream, then changes sign. As such, the flame's near and farfield vorticity distribution is controlled by shear and baroclinic vorticity, respectively. These points are clearly seen in Figure 4 (right), which shows the axial reduction in vorticity along the mean flame front (for location of mean flame front see Figure 3).



Figure 4: (Left) Transverse variation of vorticity magnitude with and without acoustic excitation at height y=0.5D downstream of bluff body. (Right) Variation of vorticity magnitude along mean flame front position.  $U_o = 1.8$  m/s,  $\phi = 0.8$ . For the acoustically forced case,  $St_D = 1.59$ ,  $u'/U_o=0.5$ .

Periodic flame perturbations are continuously being generated and propagated in the mean flow direction. As noted above, the amplitude of this fluctuation varies with height, due to the growth and decay of the underlying flow structures as well as the propagation of the flame, which tends to smooth out the wrinkles. Several results showing the typical variation of  $L'(y, f_o)$ , defined as the amplitude of the flame front wrinkle at the frequency of excitation  $(f_o)$ , for a fixed axial location y, are shown in Figure 5. This graph shows that the amplitude of flame corrugation initially grows downstream with distance, reaches a maximum and then decays. This decay is rapid, i.e. at large distances, around six convective wavelengths or so downstream, no significant coherent responses are present in the flame front spectra. The corresponding phase linearly varies with downstream distance, indicating a constant propagation speed [8]. The slope of a best fit line through this phase shows that this convection speed is nearly equal to the mean axial flow velocity,

As shown by Shanbhogue *et al.*[8], this initial growth in amplitude of flame response is due to flame holding at the bluff body - i.e., even though the flow is oscillating, as long as the flame remains fixed at its attachment point, it will not develop wrinkles at this point. Moving downstream, the amplitude of wrinkling grows. The decay in amplitude is due to two factors. First, flame propagation normal to itself is continuously acting to smooth out the wrinkles. If the flow disturbance persists downstream, some sort of equilibrium develops whereby flow disturbances wrinkle the flame and flame propagation smoothes the wrinkle out. However, due to the decay in vorticity field downstream discussed above, due to baroclinic vorticity and diffusion, the excitation field decays.

In general, the structure of these flame corrugation envelope curves varies with frequency, flow velocity, and bluff body characteristics. However, similar response curves should be obtained if the underlying velocity fields are similar. To verify this, experiments were performed at conditions with the same ratio of forcing frequency to the most amplified shear mode frequency,  $f_o/f_{SL}$ , where  $f_{SL}$  was calculated using the relation<sup>10</sup>:  $f_{SL} = 0.0235 f_K (Re_D)^{0.67}$ . Results are shown below for two different flow velocities, corresponding to  $f_o/f_{SL}=1.41$  and 0.37. In contrast, if the same procedure were repeated for similar values of  $f_o/f_K$ , then the response curves do not overlap [8]. This result provides further evidence that the velocity field disturbing the flame is dominated by excitation of shear modes.



Figure 5: Coherent Response for  $f_o/f_{SL}$ =1.41 and  $U_o$  = 2.27 (left) and  $f_o/f_{SL}$ =0.37 and  $U_o$  = 4.47 (right). The values of different parameters for each case (B thru D) are enumerated in Table 1.

Table 1. Values of parameters for data used in Figure 4.								
Case	Diameter ( <i>D</i> ), <i>mm</i>	Velocity (U <sub>o</sub> ), m/s	Reynolds Number ( <i>Re<sub>d</sub></i> )	Excitation Frequency (f <sub>o</sub> ), Hz	Excitation Amplitude $\frac{u'}{U_o}$	$St = \frac{f_o D}{U}$	$f_{SL}$ , $Hz$	$\frac{f_o}{f_{SL}}$
В	9.52	2.2710	1250	200	0.0094	0.84	140.16	1.42
С	12.7	2.27	1667	180	0.013	1.01	127.47	1.41
D	12.7	4.47	3283	150	0.0063	0.43	395.25	0.37
E	9.52	4.47	2462	165	0.0069	0.35	434.61	0.37

#### Table 1: Values of parameters for data used in Figure 4.

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