Optical Evaluation of Combustion Noise Source Terms

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Theme

The physicochemical processes believed to be responsible for noise generation in turbulent combustion have been described in terms of several alternate analytical models. Strahle[1,2] adopted the Lighthill-type wave operator formulation to obtain semiempirical expressions for acoustic power based on the wrinkled flame model and the distributed reaction model. Chiu and Summerfield[3] adopted the convected wave equation approach and employed the method of multizones to account for nonhomogeneities and source convection within the flame zone. This latter theory, as a result of its less restrictive approach, contains several source terms not found in the Strahle theory. In the work described herein, measurements have been made to compare the magnitude of one of the additional terms found in the Chiu-Summerfield theory with that of the term found in Strahle theory. It is found that they are of comparable intensity for some flame conditions.

Contents

The theory of combustion noise developed by Chiu and Summerfield[3] gives the far-field noise intensity due to a turbulent flame as

$$I=(I_f/r^2)\Sigma R_{ij} \tag{1}$$

where I_f is a combination of flame parameters, r is the distance between the flame and measurement point, and

$$R_{ij}=\int_{V(\alpha)}\int_{V(\beta)} S_{ij}(\alpha,\beta)\,\mathrm{d}V(\alpha)\,\mathrm{d}V(\beta) \tag{2}$$

in which α and β are position coordinates of the source terms, and S_{ij} consists of six terms involving time and spatial derivatives of the heat release rate multiplied by combinations of mean and fluctuating velocity and temperature components. The two terms to be compared in this paper may be written as follows:

$$S_{11}=[\partial\dot{Q}'(\alpha)/\partial\tau]\,[\partial\dot{Q}'(\beta)/\partial\tau] \tag{3}$$

$$S_{12}=2u_i(\alpha)\,[\partial\dot{Q}'(\alpha)/\partial\xi_i]\,[\partial\dot{Q}'(\beta)/\partial\tau] \tag{4}$$

where $\dot{Q}'$ is the time-varying component of the rate of heat release, τ is a dimensionless time, u_i is a velocity component, and ξ_i is a dimensionless distance in the i direction.

Presented as Paper 76-38 at the AIAA 14th Aerospace Sciences Meeting, Washington, D.C., Jan. 26-28, 1976; submitted Feb. 3, 1976; synoptic received April 2, 1976. Full paper available from AIAA Library, 750 Third Avenue, New York, N.Y. 10017. Price: Microfiche, $2.00; hard copy, $5.00. **Order must be accompanied by remittance.** This research was sponsored by the Office of Naval Research Contract N00014-75-C-0507 issued by the Power Branch of the Office of Naval Research.

Index categories: Aircraft Noise, Powerplant; Combustion in Gases.

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The S_{11} term is common to both analytical models, whereas the other five S_{ij} terms including S_{12} appear only in the Chiu-Summerfield theory. The additional terms result from the use of the convected wave equation and suggest that nonsteady flame inhomogeneities are coupled by means of the flow, resulting in additional noise sources.

To test the validity and importance of this effect, an optical method of monitoring source terms through radiation measurements has been used. John and Summerfield[4] concluded that CH and C_2 radicals, although playing a minor role in a combustion reaction, can serve as tracers for the more important chemical processes occurring in the flame. Measurement of time and spatial variations of these emissions, using appropriate focused optics and associated differentiating electronics, provide the time and spatial variations of the heat release rate within the flame. Such measurements, together with information regarding mean velocity gradients in the flow, allow the determination of S_{11} and S_{12} and allow comparisons of magnitudes to be made.

The measurement of $\partial\dot{Q}(\alpha)/\partial\tau$ is made by focusing the radiation from a fixed, small volume of the flame onto a photodetector and time-differentiating the output. A second detector that scans the regions of the flame determines $\partial\dot{Q}'(\beta)/\partial\tau$. The cross-correlation of the differentiated output of the two photocells is measured for a group of α, β combinations. The quantity of $\partial\dot{Q}'(\alpha)/\partial\xi_i$ is obtained by subtracting the output of a pair of photo-detectors kept at a small, fixed distance apart. A second pair of detectors focused on the flame similarly yields $\partial\dot{Q}'(\beta)/\partial\tau$. The region of the flame contributing to the measurements is kept small by using small f number optics and "pinholes" in front of the detectors.

The flame being examined is a premixed propane-air flame stabilized by a 1/4-in. (0.632-cm)-diam burner by means of a hydrogen pilot flame (Fig. 1). The burner has removable upstream grids to produce turbulence of varying scale and intensity.

In order to evaluate S_{12}, mean velocities in the flame must be known. Mean and turbulence velocities along the jet centerline were measured for the case of no burning, but with equivalent gas flow rates. Durst and Kleine[5] have shown that the flame has only a modest accelerating effect on the mean velocity and enhances the streamwise fluctuation only slightly while giving a slightly different transverse velocity fluctuation distribution from that observed in a nonburning jet. For a first approximation, the nonburning mean and turbulence velocities will be used.

Figure 2 shows the raw data obtained based on the CH band radiation as measured at the point (0,4,0), with one photomultiplier focused on that point and the other being traversed in the axial direction around that point, for one flow condition. The maximum in the $\epsilon_{\dot{a}\dot{b}}$ curve occurs where the two photomultipliers are focused on the same point in the flame. Similarly, the value of $\epsilon_{(a-b)\cdot(\dot{b})}$ is zero at this point, since the difference in the two readings is zero. The peak in the $\epsilon_{\dot{a}\dot{b}}$ curve is proportional to S_{11}, whereas the slope of the $\epsilon_{(a-b)\cdot(\dot{b})}$ is proportional to $\partial\dot{Q}'(\alpha)/\partial\xi_i\cdot\partial\dot{Q}'(\beta)/\partial\tau$, which is the S_{12} term without the mean velocity factor.

Table 1 gives a tabulation of the raw data of $(\epsilon_{\dot{a}\dot{b}})_{\max}$ and the slope $\Delta\epsilon_{(a-b)\cdot(\dot{b})}$ for two flow conditions and at two points in the flame for each condition. Since the two numbers

Table 1 Comparison of $\bar{S}_{11}$ and $\bar{S}_{12}$ at two points for two flow conditions

	$(\epsilon_{\dot a \dot b})_{max}$, $(V/sec)^2$	$\bar{S}_{11}\cdot 10^{-4}$ $(V/sec)^2$	$\Delta\epsilon_{(a-b)\cdot\dot b}$, $V^2/m\text{-}sec$	v_y, m/sec	$\bar{S}_{12}\cdot 10^{-4}$, $(V/sec)^2$
$\alpha=\beta=(0,4,0)^a$					
Condition A (1483 scc/sec)	3.35	12.4	66.0	32.0	10.2
Conditon B (2476 scc/sec)	5.0	18.5	80.0	53.3	20.6
$\alpha=\beta=(0,10,0)^a$					
Conditon A (1483 scc/sec)	4.8	17.8	122.0	15.5	9.1
Condition B (2476 scc/sec)	10.0	37.0	122.0	25.8	15.2

[a]Dimensions in centimeters; see Fig. 1.

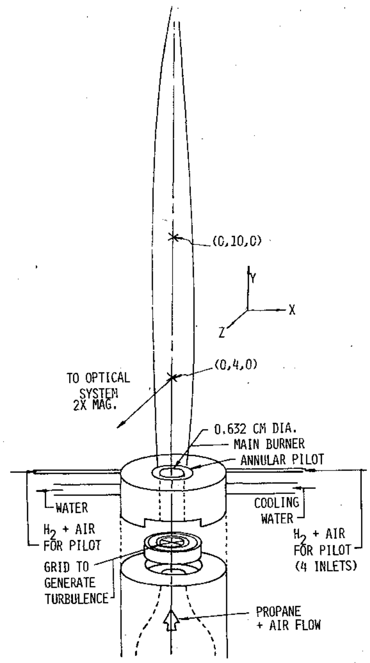

Fig. 1 Schematic diagram of burner and luminous flame, showing the two measuring points in relation to the luminous flame zone.

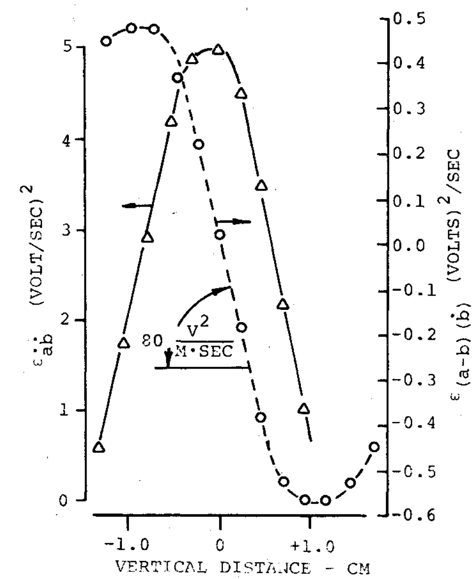

Fig. 2 Output of electronics that operated on the output of photomultiplier tubes monitoring CH radiation at (0,4,0) in the flame for condition B; $\epsilon_{\dot a\dot b}$ is proportional to $[\partial\dot Q'(\alpha)/\partial\tau]\cdot[\partial\dot Q'(\beta)/\partial\tau]$, and the slope of $\epsilon_{(a-b)\cdot(\dot b)}$ is proportional to $[\partial\dot Q'(\alpha)/\partial\xi]\cdot[\partial\dot Q(\beta]/\partial\tau]$.

are obtained by different electronic manipulations, a different factor is needed to extract the S_{ij} terms from the raw data. After accounting for these various factors, it can be shown that $\bar{S}_{11}=3.7\times10^4\epsilon_{\dot a\dot b}$, and $\bar{S}_{12}=48.4\ v_y\cdot\epsilon_{(a-b)\cdot(\dot b)}/(\Delta y)_{optic}$, where the slope is measured in the optical plane, as shown in Fig. 2. Also shown in Table 1 are the results of this manipulation for each of the raw data shown.

The numerical values for $\bar{S}_{11}$ and $\bar{S}_{12}$ shown in Table 1 demonstrate that, near the burner tube exit, the two terms are of comparable magnitude for both flow rates examined, whereas further downstream the $\bar{S}_{11}$ term is about twice the magnitude of $\bar{S}_{12}$. From Fig. 2, one can deduce that the sizes of the coherent regions for the two sources are also of comparable magnitude. The relative contribution to the sound intensity made by each source is obtained by integrating the $\bar{S}_{ij}$ term over the source volume, as given in Eq. (2), to obtain the R_{ij} terms. It is the comparison of the R_{ij} terms which is the test of the relative importance of each as a source of noise.

Whereas the work done to date has not completed the comparison by computing the R_{ij} terms directly, it may be inferred that, with approximately equal coherent regions, as shown in Fig. 2, and with comparable sizes of the S_{ij} terms, as shown in Table 1, the R_{11} and R_{12} terms will be of approximately equal importance in the region near the burner tube exit. Further scanning of the flame is needed to evaluate the integrated effect over the entire flame volume of each of these two source terms and to establish scaling functions of each with variation of combustor conditions.

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