ACTA STEREOL 1994; 13/1: 221-226
PROC 6ECS PRAGUE, 1993
ORIGINAL SCIENTIFIC PAPER

TIME-FREQUENCY DISTRIBUTION AND IMAGÉ PROCESSING: AN APPLICATION TO THE COMBUSTION FIELD

Guy Courbebaisse

ICPI-CPE, 31, Pl. Bellecour, 69288 Lyon Cedex 02, FRANCE
CRMT, 3, Chemin de la Brocardière, 69570 Dardilly, FRANCE

ABSTRACT

The aim of this study is to provide a better understanding of the turbulent flow field inside an internal combustion engine (Floch, 1990) by measuring the "integral length scale", with a known optical method and essentially with new theoritical tools in both image processing and signal processing.

A photographic plate located at the viewing screen of a transparent combustion room, records density gradient which depends of the medium encountered by the light (Schlieren method). Such a method displays density gradients in terms of light intensity. Image processing methods are used to point out turbulence structures. In fact, a cross-correlation function is investigated to shape a new image with pseudo periodicity which contains the size information. Eventually, time-frequency distribution is introduced to determine integral length scales. The Wigner-Ville distribution is chosen to allow the analysis of "ghost terms", also named "interference fringes" (Flandrin and Escudié, 1985), giving a reliable estimation of structures size, with a convenient accuracy.

In addition, comparisons with laser Doppler velocimetry (L.D.V.) measurements are given (Fraser and Bracco, 1989). Futhermore, the dispersion of engine cycles can be estimated by taking into account both the spark gap adjustment of the sparking plug and the average of integral length scales.

Keywords: integral length scale, image processing, time-frequency distribution.

INTRODUCTION

Many researchers have performed measurements of integral length scales with either the hot-wire anemometry method or with the laser Doppler velocimetry method (Fraser and Bracco, 1989). Physically, an integral length scale represents an average of all the length scales present in a flow. The purpose of the present study is to show in a non-classic way, the correlation between the dispersion of combustion cycles (statistical point of view) and the integral length scale (Hires et al., 1978).

Fig. 1 gives an example of a 3-dimensional statistical analysis of heat release. The heat release (z-axis), seen as the liberated energy, is expressed in terms of crankshaft degree (x-axis), and of percentage over 800 combustion cycles (y-axis).

In this experiment a transparent cylinder head is used, allowing the study of flow structures by an optical method that will be described in what follows. Fig. 2 shows the Schlieren system (Baritaud, 1987). When the air gas mixture is established inside the transparent cylinder head of width "L", named test section in Fig. 2 (x-y plane), the incident light ray "ε" may be expressed by:

$$\varepsilon = \frac{L}{R} = L \,\mathrm{grad}\, n \qquad (1)$$

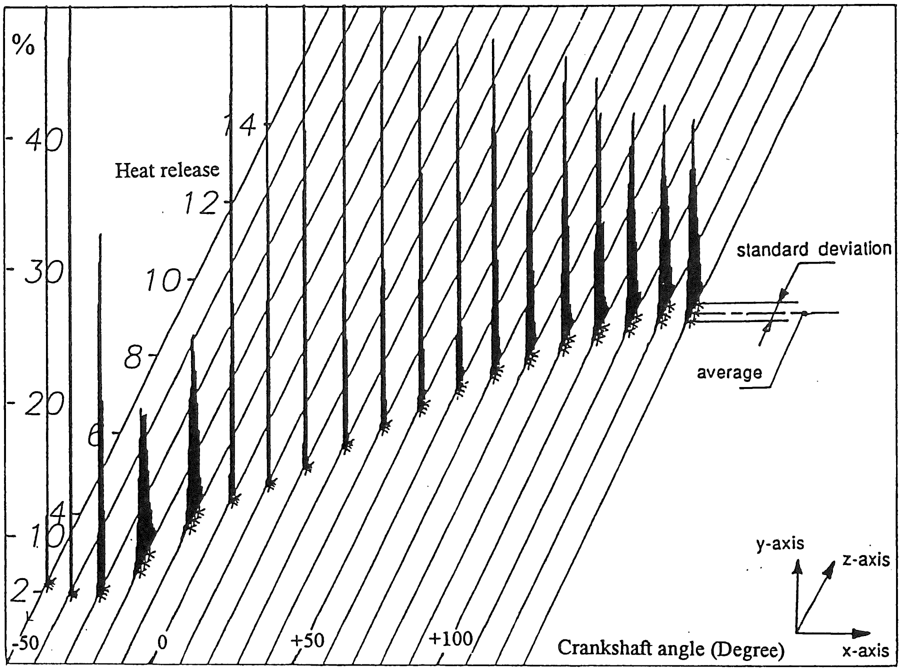


Fig. 1. Heat release over 800 engine cycles.

where "n" is the index of refraction of the medium and "R" is the curvature radius of the incident light rays. Because the "knife-edge" (Fig. 2) is fixed in the y-direction, the density gradients in x-direction are displayed. As shown in Fig. 3, this optical method provides the first derivative of the density function "ρ". Hence:

$$\varepsilon_x = L\frac{\delta n}{\delta x} = L\,K_{G\text{-}D}\frac{\delta \rho}{\delta x} \qquad (2)$$

where $K_{G\text{-}D}$ is the Gladstone-Dale constant ($K_{G\text{-}D} = (n - 1) / \rho$) for a given gas.

EXPERIMENTAL PROCEDURE

The engine is a single cylinder one, which is operated at 1,000 rotations per minute. The "compression ratio", defined by the ratio of cubic capacity plus compression capacity over compression capacity, is equal to 7.3. The Air-Propane gas mixture(C_3H_8) is used to perform combustion cycles. Spark gap is about 1 mm.

The image processing system consists of a specialized addendum card, named "P.C. OEIL", inserted in a PC compatible system and of an image processing program"VISILOG". Signal processing is realized on the same computer, equiped with a "time-frequency distribution" program.

Schlieren method is set up to allow the incident light to pass through the transparent combustion room. Simultaneously, engine pressure are measured from 50 degrees before top dead center (T.D.C.) to 100 degrees after T.D.C. allowing statistical analyses of combustion cycles (Fig. 1) and Schlieren images are recorded with a high speed camera (6,000 pictures per second), on a 16mm high speed tungsten film. Developed films are viewed, through specific lens, by a coupled charge device (C.C.D.) camera which, in turn, is

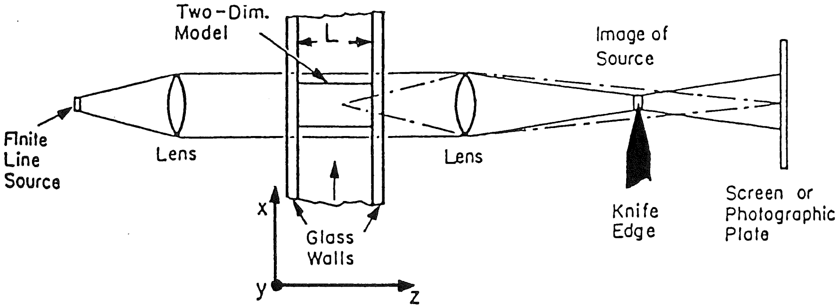


Fig. 2 Schlieren system.

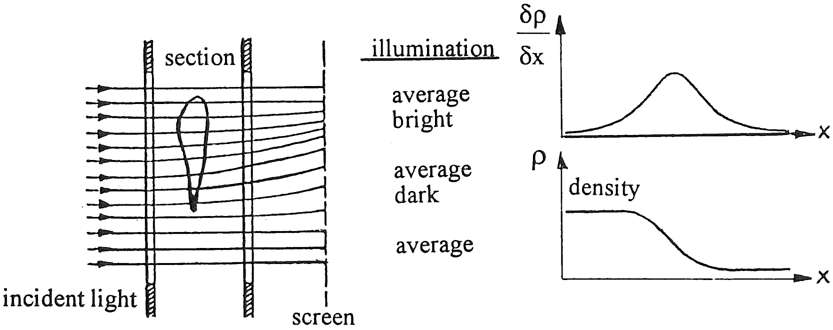
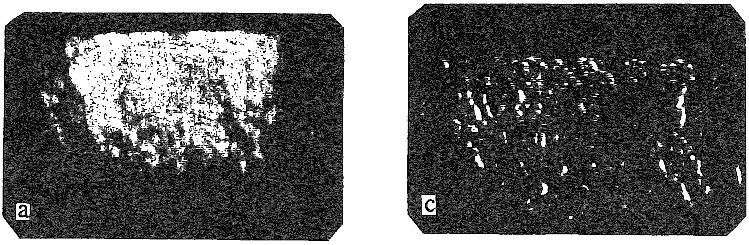
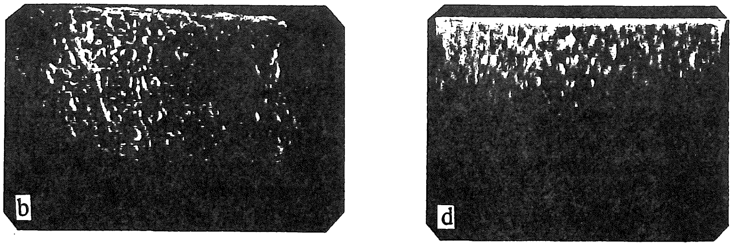


Fig. 3. Schlieren principle.



raw image

Turbulence structures image



Sobel gradient image

Correlation image

Fig. 4. Four steps of images processing.

connected to the image processing system.

By using the image processing system, four digital images are successively obtained as shown in Fig. 4. The first one, "a", shows the raw image after digitization. The second one , "b", corresponds to the Sobel gradient of the "a" image (Coster and Chermant, 1985). The third one, "c", is the result provided by the superposition of "a" and "b" images $((a^2+b^2)^{1/2})$, followed by a line erosion operation, where B is a linear structuring element:

$$c = ((a^2 + b^2)^{1/2}) - E^B((a^2 + b^2)^{1/2}) \tag{3}$$

The fourth one, "d", showing structure's periodicity, is provided by computing cross-correlation function (Jourlin and Schon, 1988), performed on each column "x" of the "c" image, defined by:

$$C_{xx}(\tau) = \frac{1}{T}\int_0^T x(t)\,x(t-\tau)\,dt \tag{4}$$

Then, Wigner-Ville distribution is computed for each column of the resulting cross-correlation image (Fig. 4 d), in the following way:

$$WV_x(t,\nu) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right)x^*\left(t-\frac{\tau}{2}\right)e^{-2i\pi\nu\tau}d\tau \tag{5}$$

The Wigner-Ville distribution is a time-frequency one (Flandrin and Escudié, 1985), used here in analogy as a space frequency method. The purpose of this distribution is to exhibit time-varying spectral properties in the case of non-stationnary processes. It should be remembered, that the Wigner-Ville distribution (Eq.5) is bilinear. This property produces inherent "ghost terms" or "interference fringes". Here, the interference fringes (Fig. 5) come from the interaction between average grey level "y" (direct current (D.C.)) of the considered image and the "corresponding harmonic of the turbulence structures". Thus, the image presented in Fig. 5 may be seen as the result of the superposition of the Wigner-Ville distribution of each component and of the Wigner-Ville one of interference fringes due to the two components "x" and "y", such that:

$$W_{x+y}(t,\nu) = W_x(t,\nu) + W_y(t,\nu) + 2\,\mathrm{Re}\left\{W_{xy}(t,\nu)\right\} \tag{6}$$

These interference fringes visible in Fig. 5, give the period of structures or the size of turbulence structures for one crankshaft angle. The same operation has to be performed for each crankshaft angle around the T.D.C. to obtain a graph such as Fig. 6.

RESULTS AND THEIR ANALYSIS

The correlation function and the Wigner-Ville distribution seem best suited to quantify integral length scale. Fig. 5 reveals interference fringes. As a matter of fact, the size of turbulence structures fluctuates between 0.82 mm and 0.86 mm. Fig. 6 express these data in terms of crankshaft angle; This size is similar to the size provided by the L.D.V. method (Fraser and Bracco, 1989). Yet, the drawback of this L.D.V. method is to use empirical cut-off frequency (450 Hz) to filter the signals of turbulence structures from those of all fluctuations (Fig. 6).

Experimental results, issued from this original analysis, show that the dispersion of combustion cycles (Fig. 1, statistical view) became stable when the ratio "Useful space over size of structures" reached unit value. Fig. 7 expresses this last ratio in terms of dispersion of heat release over 800 cycles (standard deviation over average). By "useful space" is

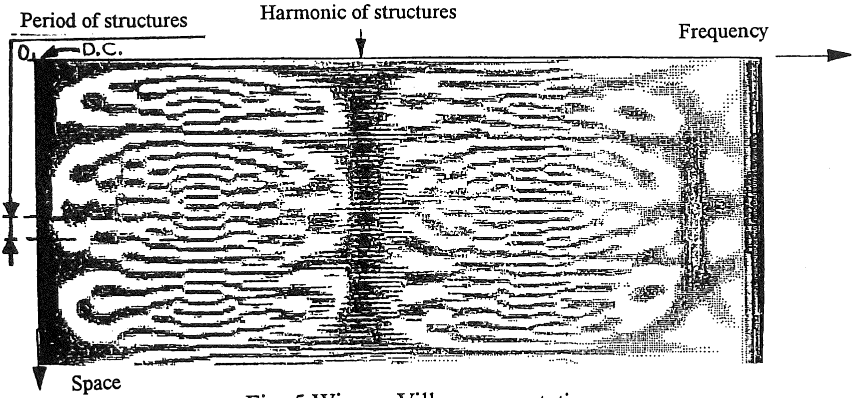


Fig. 5. Wigner-Ville representation.

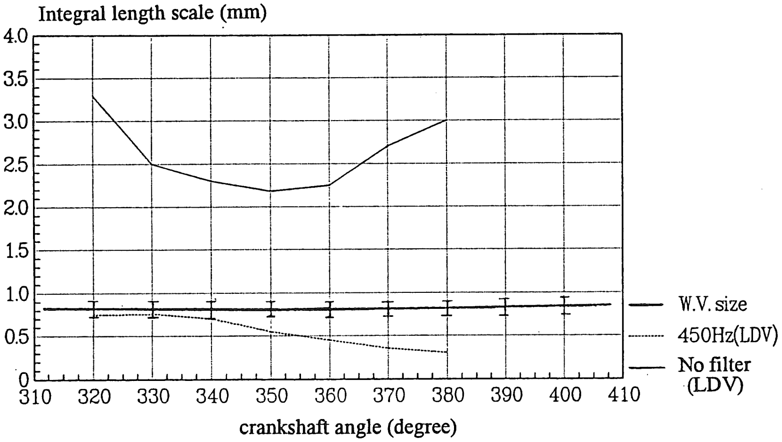


Fig. 6. Sizes of integral length scale.

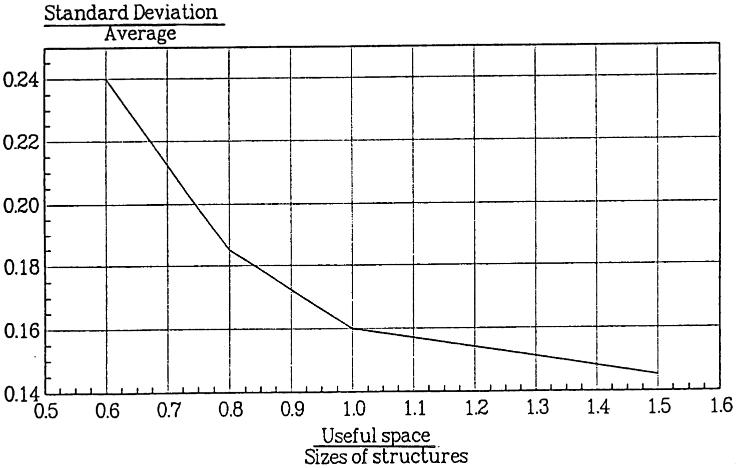


Fig. 7. Dispersion of combustion cycles.

meant spark gap minus cold layer. The cold layer, or range where ignition is impossible, can be estimated to 0.2 mm. The spark gap is adjusted to 1mm; Hence, in this case, the useful space is equivalent to 0.8 mm. The average size of structures (see Fig. 6), is estimated to 0.84 mm. For this reason, the ratio "Useful space over size of structures" is closed to unity as shown by Fig. 7. In this case, the integral length scales are smaller than the spark gap; consequently, the standard deviation over 800 combustion cycles is small (Fig. 1).

CONCLUSION

The Wigner-Ville distribution allows a reliable estimation of the size of turbulence structures. In the same way, bilinear time-scale distributions seem very suited to give convenient parameters by using their interference fringes (Courbebaisse, 1993). These distributions are invariant to time shifts and to time frequency scalings. Besides, a fractal investigation should be performed to determine whether turbulence structures can be estimated by one fractal range (Mandelbrot, 1968) for different configurations of the engine. Also, the Chaos and Catastrophe theories underline the sensitivity to initial condition in the case of nonlinear media (Poston and Stewart, 1978). Here, the initial ignition of the combustion and its evolution depend on the size of turbulence structures. Data on the latter phenomenon will be of high relevance for models of combustion (Mantel, 1993). By this paper, the author would like to make engineers and researchers aware of the fact that emergent techniques like the Wigner-Ville distribution can cross-fertilize new fields of applications.

REFERENCES

Baritaud T. Optical methods inside internal combustion engine. Journée d'étude de la S.F.T., Institut.Française de Pétrole, Rueil-Malmaison, Fr., January 1988: 1-19.

Coster M, Chermant JL. Précis d'analyse d'images, Paris:CNRS, 1985.

Courbebaisse G. Transformée bilinéaire temps-échelle des signaux asymptotiques d'énergie finie, 14 ème coll. GRETSI sur le traitement du signal et ses applications, Juan-les-pins, Fr., September 1993; 1: 41-4.

Davis MR. Identification of regular disturbances in turbulence by a modified Schlieren method. In: Véret Cl. ed. Proceedings of the Fourth International Symposium on Flow Visulisation, New York: Springer-Verlag, 1986; 4: 51-6.

Flandrin P, Escudié B. Principe et mise en oeuvre de l'analyse temps-fréquence par transformation de Wigner-Ville, J. Traitement du Signal, 1985; 2: 144-51.

Floch A. Etude de la turbulence instationnaire dans une chambre de combustion à volume constant. Thèse de physique. Université de Rouen, July 1990.

Fraser RA, Bracco FV. Cycle-resolved LDV integral length scale in an IC engine. Princeton University. S.A.E. 890615, Warrendale: SAE*, 1989; 1091-115.

Hires SD et al. The prediction of ignition delay and combustion intervals for a homogeneous charge. Ford company. S.A.E. 780232, Warrendale: SAE*, 1978; 1-15.

Jourlin M., Schon JP et al. Apports des techniques de traitement d'image à la visualisation d'écoulements. Revue Générale de Thermique,Fr., 1988; 320-321: 464-8.

Mandelbrot B, Van Ness J. Fractional brownian motions, fractional noises and applications. SIAM Review, October 1968; 10/4:422-37.

Mantel Th. Turbulent combustion modelling in spark ignition engines. Thèse de physique. Université de Rouen, January 1993.

Poinsot T, Trouvé A, Veynante D, Candel SM, Exposito E. Phase average imaging in combustion instability studies. In: Véret Cl. ed. Proceedings of the Fourth International Symposium on Flow Visulisation, New York: Springer-Verlag, 1986; 4: 741-6.

Poston, Stewart. Optics and scattering theory. Catastrophe theory and its applications. London: Pitman, 1978; 246-83.

Smith JR. The influence of turbulence on flame structure in an engine. In: Uzkan T ed. New-York: ASME, 1983; 67-72.

* : S.A.E. : Society of Automative Engineers