# Characterization of the spray dynamics in a Diesel engine using optical imaging and active contour approach

Katarzyna Bizon<sup>1</sup>, Gaetano Continillo<sup>1,2</sup>, Ezio Mancaruso<sup>2</sup>, Bianca M. Vaglieco<sup>2</sup> <sup>1</sup>Università degli Studi del Sannio, Benevento, Italy <sup>2</sup>Istituto Motori CNR, Naples, Italy

#### **1** Introduction

The reduction of exhaust emission and potential savings of the primary energy source in the automotive application are of the great interest in view of both environmental regulations and economical benefits. Therefore, special attention should be paid to the analysis of the fuel spray characteristics in high speed direct injection engines, in order to understand how the use of different fuel and system parameters influences emissions and thermal efficiency of the engine. The behavior of spray jets has been addressed earlier [1-3] in terms of commonly used parameters such as the spray tip penetration S, the spray cone angle  $\theta$  and the spray tip velocity U, and the correlation of these characteristics with fuel properties, injection parameter and in-cylinder condition. The detailed analysis of the jets behavior is realizable using a transparent diesel engine [1] which, in connection with available imaging techniques employing high speed digital cameras, permits to follow the evolution of the fuel jets with both high spatial and temporal resolution. As the amount of collected data is generally huge, a manual identification of the jet contours would be extremely time consuming. Hence, it would be useful to develop the some algorithm for contour detection in the collected spray images. Then the requested parameters, i.e. spray tip penetration or cone angle, can be easily identified from the detected contour. Over the last two decades, a number of edge and line oriented methods for contour detection have been proposed [4] based on various approaches, from basic concepts related to differential contrast-based methods, statistical approaches utilizing image texture information, and many others.

In this work, optical measurements have been employed to study fuel spray behavior in a single cylinder transparent research engine. The jet tip penetration have been determined using an automatic procedure based on the active contour algorithm for contour detection [5]. The results obtained were then compared with the data determined manually by simply cutting off jet shapes from the images, and relatively good agreement can be observed.

## 2 Experimental setup and procedure

Experiments were conducted on a single cylinder Diesel engine (Figure 1a) equipped with head and Common Rail (CR) injection system of the four cylinder, 16 valves 1.9 l standard production engine. Engine specifications are reported in Table 1 and some more details can be found in [1]. The fuel – commercial Diesel fuel – has been injected through a injector with 8-hole nozzles, 0.136 mm orifice, 480 cc/30 s at 100 bar flow number, 148° cone opening angle (minisac type). The injector has been



Figure 1. Research engine (a) and scheme of the experimental optical setup (b).

controlled by a fully flexible Electronic Control Unit (ECU) for combustion optimization. In order to provide a full view of the combustion bowl a 46 mm diameter flat window has been fitted in the piston head and an appropriate 45° visible fixed mirror has been set inside the extended piston (Figure 1b). The window has been realized with UV-grade fused silica.

Stroke	92 mm
Bore	85 mm
Cylinder displacement	$522.1 \text{ cm}^3$
Valve pockets	$5.6 \text{ cm}^3$
Bowl volume	$19.70 \text{ cm}^3$
Cylinder dead volume	$41.25 \text{ cm}^3$
Compression ratio	16.52:1

Table 1: Engine specifications

Measurements were performed at engine speed of 1500 rpm at 2 bar of brake mean effective pressure (BMEP). The implemented injection strategy consisted of pilot and main pulses, with the start of injection (SOI) of the pilot pulse at  $15^{\circ}$  before top dead center (BTDC) and the main pulse at  $4.5^{\circ}$  BTDC. In order to obtain images with well visible jets of the fuel, experiments were conducted with a high percentage of the exhaust gas recirculation (EGR) of 70%. Moreover, two halogen lamps have been used to light the combustion chamber during the injection process, and the acquisition of the digital images has been performed by means of a charge coupled device (CCD) camera with a resolution of  $640 \times 480$  pixels. The camera had a high sensitivity over a wide visible range and it has been equipped with a 55 mm objective F/1:3.5. Images have been acquired with an exposure time of 55 µs and 41 µs, corresponding to  $0.5^{\circ}$  crank angle (CA).

#### **3** Active contours

The concept of *active contours*, or so-called *snakes*, proposed by [5], is generally based on the variational approach to the identification of image contours or edges. The concept is based on the evolution of the dynamic curve, which can be initiated by the user around some object, to the object boundaries induced by the action of some internal and external "*forces*".

A snake is a curve  $\vec{v}(s) = [x(s), y(s)]^T$ ,  $s \in [0,1]$  that moves through the spatial domain of an image to minimize the energy functional:

$$E\left[\vec{v}(s)\right] = \int_{0}^{1} \frac{1}{2} \left[\alpha \left|\frac{\partial \vec{v}(s)}{\partial s}\right|^{2} + \beta \left|\frac{\partial^{2} \vec{v}(s)}{\partial s^{2}}\right|^{2}\right] ds + \int_{0}^{1} E_{ext}\left[\vec{v}(s)\right] ds$$

This functional can be viewed as a representation of the energy of the contour, and the final shape of the contour corresponds to the minimum of this energy. The first term of the functional refers to the internal energy of the image which controls the smoothness of the curve, with  $\alpha$  and  $\beta$  being positive parameters which refer to the tension and rigidity of the snake. The second term is the external deformation energy and represents the effect of the "forces" that are not intrinsic properties of the contour, but in fact contain all information on the image properties.

For a gray level image, I(x,y), a typically used external energy formulation, called also *edge map*, is given as [5]

$$\Omega(x, y) = -\Gamma \left| G_{\sigma} * \nabla I(x, y) \right|^{2}$$

where \* is the convolution operator,  $G_{\sigma}$  is a two-dimensional Gaussian function, used here for noise filtering, with standard deviation  $\sigma$ , and  $\Gamma$  is a positive weighting parameter. Since it is well known – in image processing – that removing noise by means of a Gaussian filter leads to blurring of natural edges, an improvement of this rather classical image denoising method has been proposed [6]. Namely, a nonlinear anisotropic diffusion filter – which provides more smoothing within a region rather than across boundaries – has been introduced. The idea is to treat the image intensity as a fluid concentration, hence a simplified expression of the anisotropic diffusion can be employed:

$$\frac{dI}{dt} = \operatorname{div}\left\{\kappa(x, y, t) \cdot \nabla I(x, y)\right\}$$

where  $\kappa$  is a diffusion coefficient that can be determined in many ways. Here we use a decreasing diffusivity function [6]:

$$\kappa(x, y, t) = f\left\{\nabla I(x, y, t)\right\} = \frac{1}{1 + \left(\left\|\nabla I\right\|/\lambda\right)^2}$$

where  $\lambda$  is a positive constant controlling diffusion across boundaries. The problem of minimization of the functional can be solved by solution of the appropriate Euler-Lagrange equation [4]. When the original formulation of the problem is considered, multiple local energy minima may exist, making the outcome of the method sensitive to the initial conditions. To overcome this problem, a gradient vector flow (GVF) approach was proposed, in which the traditional external force  $E_{ext}$  is substituted by the GVF field derived from the gradient vectors of the image edge map [7]. Further improvement of the original formulation of the variational problem can be done by introducing some *a priori* information. Among the approaches proposed in the literature, a very simple an effective way that improves convergence of the active contour to the correct boundary is adding a few *directional lines* to point the direction along which the contour should evolve, and incorporating the corresponding directional forces in the functional to be minimized [7].

The procedure is illustrated with an example (Fig. 2). The algorithm is expected to detect a given shape in a bitmap image, starting from a guessed shape, with successive iterations. The red line is the initial shape, whereas the blue line is the converged final shape, describing the contour of the airship in the photograph.



Figure 2. Example of application of the contour detection algorithm. Image from a postcard representing a Zodiac III airship, 1909.

# 4 Results and discussion

In Figure 3 some images of the main injection are reported. The start of visible injection occurs at about  $3^{\circ}$  BTDC where the presence of the eight jets begins to be visible. As it can be observed in the subsequent frames showing jets evolution, no fuel impingement phenomena have been detected for the considered engine conditions and fuel used.



Figure 3. Sequence of typical images of the Main injection.

Figure 4 present results of the application of two traditional algorithms for edge detection, particularly the Sobel operator (Fig. 4a) and Canny edge detector (Fig. 4b). As it can be clearly seen, both algorithms exhibit poor performance, in that they are unable to distinguish among external and internal edges. It is concluded that an approach using some prior knowledge of the object to be identified, such as for example the fact that the contour is expected to surround a simply connected domain, must be adopted.



Figure 4. Edges determined using Sobel operator (a) and Canny edge detector (b).

Figure 5a shows a typical result obtained by using the proposed active contour algorithm for the identification of jet contours. The red curve corresponds to the initial snake, i.e. the first guess for the jet contour, which in this phase of the work is initiated by the user, whereas the blue curve is the jet edge obtained by the algorithm. Figure 5b shows the penetration curve versus crank angle for the main injection calculated from the jets contours determined using the active contour algorithm, compared with jets penetration obtained manually by simply cutting off of the jet contours from the images.



Figure 5. Jet contour at 1° BTDC determined using active contour algorithms (a) and comparison of the jets penetration versus crank angle for main injection determined manually and automatically (active contours).

In our computations the parameters which refer to the extensional and flexural rigidities of the snake, were set as  $\alpha$ =0.05 and  $\beta$ =0.05 respectively. The larger the values of  $\alpha$  and  $\beta$ , the smoother the front of active contour becomes: in fact, as their values are decreased, the contour gains freedom in movement. Figure 6a presents jet contours obtained using different values of the extensional rigidity  $\alpha$  in the range from 0 to 0.2, while in Figure 6b corresponding values of the jet penetrations versus  $\alpha$  are reported. Compared to the manual procedure, active contours are obviously much faster. With no attempt to code optimization, the elapsed time for the case shown in Fig. 4 is 32.5 seconds on an Intel Core 2 Duo at 3.00GHz.



Figure 6. Jet contour at 1° BTDC for different values of  $\alpha$  (a) and corresponding values of jet penetration length.

## 5 Conclusions

A variational approach employing so-called "active contours" (or "snakes") was proposed and tested for the semiautomatic determination of fuel jet tip penetration distance. The algorithm at present requires the manual initialization with an initial "snake". The results obtained compare favorably with the data determined manually by simply cutting off of the jet shapes form the images.

Future work will be focused on the general improvement of the algorithm in terms of accuracy, and on its full automatization, i.e. the manual initialization of the contour will be replaced by use of *jet templates*. Particularly, curve initialization will be based on empirical models of jet tip penetration and cone angles available in the literature.

#### References

- [1] Mancaruso E., Sequino L., Vaglieco B.M. (2011). First and second generation biodiesels spray characterization in a diesel engine. Fuel 90: 2870.
- [2] Kostas J., Honnery D., Soria J. (2009). Time resolved measurements of the initial stages of fuel spray penetration. Fuel 88: 2225.
- [3] Soid S.N., Zainal Z.A. (2011). Spray and combustion characterization for internal combustion engines using optical measuring techniques A review. Energy 36: 724.
- [4] Papari G., Perkov N. (2011). Edge and line oriented contour detection: State of the art. Image Vision Comput. 29: 79.
- [5] Kass M., Witkin D., Terzopoulos D. (1987). Snakes: active contour models. Int. J. Comput. Vision 1: 321.
- [6] Perona P., Malik J. (1990). Scale-space and edge detection using anisotropic diffusion. IEEE T. Pattern Anal. 12: 629.
- [7] Zhu G., Zhang S., Zeng Q., Wang C. (2010). Gradient vector flow active contours with prior directional information. Pattern Recogn. Lett. 31: 845.