Computing and Informatics, Vol. 30, 2011, 1303–1319

A NOTE ON MATHEMATICAL MODELLING OF ELLIPTICAL FIRE PROPAGATION

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Abstract. Mathematical modelling of forest fire propagation in time plays a key role in existing fire propagation predicting systems. Such systems are capable of simulating the growth of fire front in time and space and predicting spatial and temporal fire behaviour. In our previous papers, we studied mathematical foundations of the elliptical fire propagation model implemented in several advanced simulation systems. The model is based on Huygens' principle applied on fire propagation assuming locally elliptical fire spread. However, in the literature various other mathematical representations of local fire propagation have been reported, such as double ellipse, lemniskata, oval shape, tear shape, and others. Such types of local fire propagation have been experimentally observed in certain conditions during laboratory and field fires. In this paper, we demonstrate several simple examples of fire propagation corresponding both to the elliptical and non-elliptical local fire propagation in homogeneous conditions.

Keywords: Forest fire, fire behaviour, elliptical fire propagation model, single ellipse, double ellipse, tear shape, envelope, FARSITE

1 INTRODUCTION

Forest fires belong to the most destructive phenomena in forests causing great damages and significant devastation of landscape and nature environment. They also pose threats to human safety and cause tremendous damages to timber resources and other economic assets [5, 18, 30, 33, 17].

Advances in computers and informatics have enabled developing advanced models of the forest fire propagation which have become the heart of existing fire simulation systems. The fire behaviour predicting systems are capable of simulating the growth of fire front in time and are able to describe spatial and temporal fire behaviour. They also allow to quantify and often even to display several fire characteristics required for the fire effects evaluation. Research on mathematical foundations of fire propagation models and their implementations in current fire simulators is essential for better understanding the models themselves and the model limitations and assumptions, as well as how these models are used in the fire modelling systems. It is also significant for competent interpretation of simulation results and further development of such systems.

Forest fire simulation and fire behaviour modelling belong to the disciplines which have achieved significant success in the last decades. In our previous papers [14, 15, 12, 13, 31, 32], we studied existing mathematical models of forest fire propagation and the systems in which they are implemented. A variety of fire modelling systems and tools support the management of wildland fires. One of such advanced forest fire simulators is FARSITE (Fire Area Simulator) [6, 27]. It provides a two-dimensional spatial and temporal simulation of propagation and behaviour of fires under heterogeneous conditions. It links multiple empirical and deterministic models or sets of mathematical equations to predict fire growth and behaviour [26]. FARSITE incorporates existing fire behaviour models of surface fire propagation [1, 22], crown fire propagation [23, 28, 29], spotting [2], point-source fire acceleration [10], and fuel moisture [19] with spatial information on fuels, weather, and topography requiring GIS support. It produces the simulation outputs in tabular, vector and raster formats. The FARSITE system has been used in several centres of crisis management in the U.S.A. even for operational purposes.

We studied mathematical foundations of the methods implemented in FARSITE to make possible the proper use of FARSITE and its adaptation and calibration for conditions in Slovakia. Particularly, we focussed on a core module for surface fire propagation which is based on the elliptical fire propagation model [20]. This model assumes a locally elliptical fire propagation on flat terrain under homogeneous conditions. This means that a fire ignited in a point in homogeneous conditions on a flat ground propagates as a single ellipse (see Figure 1 a)). The model is based on Huygens' wave principle applied on forest fire propagation. Each new fire front is represented as an outer envelope of a set of single ellipses which represent the locally elliptical fire propagation.

In the literature, various other mathematical representations of local fire propagation have been reported (see Figures 1 b)–c)), such as a double ellipse, lemniskata, oval shape, tear shape, etc. However, the most studied representations of the fire shapes observed experimentally are the cases of single and double ellipse. Only recently, an alternative method [14, 15, 16] of the derivation of the elliptical fire propagation model was developed. This approach is based on direct application of classical procedures of the theory of envelopes of planar curves sets. The method

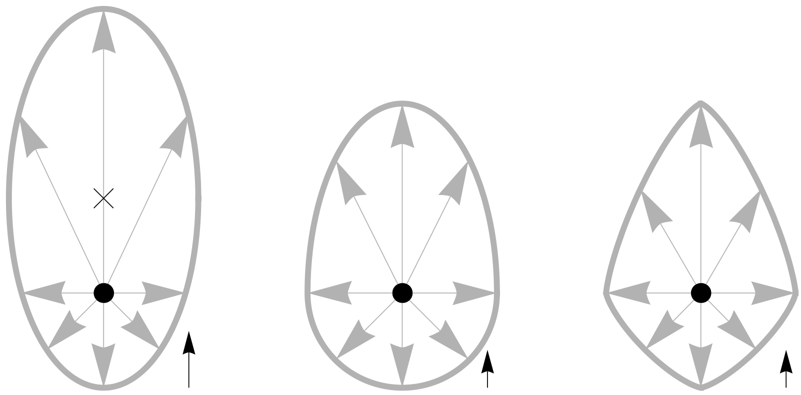

Fig. 1. Scheme of local fire propagation: fire ignited in a point on flat ground under homogeneous conditions for single ellipse a), double ellipse b) and tear drop c) cases. Black arrows represent given wind direction.

allows to derive explicit analytical formulae not only for the envelope of the set of single ellipses but also for other simple curves representing different types of the local fire propagation.

In this paper, we demonstrate several simple examples of fire propagation which correspond to both the elliptical, as well as non-elliptical local fire propagation.

2 ELLIPTICAL FIRE PROPAGATION

Vector or wave-type fire propagation models avoid problems encountered by cellular modes in dealing with spatial and temporal heterogeneity [6, 7]. With vector models, both the direction and distance of fire propagation are determined independently of the spatial input data resolution. The fire front is represented as a series of vertices that collectively define the edge of propagating fire at a particular instant of time. The environmental conditions local to each vertex are used to compute the forward fire propagation rate and direction. The fire is propagated from each vertex assuming Huygens' principle applied to a fire front which states that the fire front can be propagated using any point lying on it as an independent source of a new fire of elliptical shape. These ellipses refer to elliptical fires of a size determined by a fixed time step and the fire propagation rate local to each vertex. The orientation of these ellipses is determined by the maximum fire propagation direction. The shape of each ellipse is a function of the mid-flame wind-slope vector which determines the eccentricity of the ellipse under locally uniform conditions. The fire front is expanded over each time step and can be represented as an envelope of all such individual ellipses around the previous fire front. Because the conditions at each vertex produce independent ellipses of potentially different shapes and sizes, this technique is flexible in representing highly heterogeneous conditions encountered by fire in both space and time.

Huygens' principle has been applied to fire growth modelling in various forms. The earliest vector model was that of the radial fire propagation [24, 25] which used gridded weather inputs and a rasterized landscape of fuels and topography to provide a reasonable approximation of observed fire growth. The essential mathematics related to the wave approach was described in [3]. The technique described there appeared to be suitable as a fire growth model after comparing the simulation to experimental fire data. In [9, 8], a graphical technique was suggested which used computer graphics block-copy techniques to produce fire fronts. In [4, 8], the four-point technique was found which used four points lying on elliptical fire perimeter which correspond to its major and minor axes as the propagation points that form the new fire front. In 1990, a technique which used the points lying on the fire front polygon as the propagation points was developed [20]. This technique was then employed in the FARSITE system and is referred to in this paper as the elliptical fire propagation model. The same results were also achieved by methods in which the line segments between the vertices of fire perimeter polygon are the objects of propagation [21, 8].

Application of Huygens' principle of wave propagation on the problem of fire propagation was formulated analytically by Richards [20] who derived a non-linear system of differential equations of the first order describing the fire propagation in time. The model derivation is based on the use of a simple transform of coordinates which transforms ellipses into circles. In this case, some special geometric properties of points lying on a common tangent line of two circles can be utilized. To calculate the resulting envelope of the set of single ellipses, the ellipses are transformed into circles and the envelope of circles is obtained by spatial limiting process. The envelope of ellipses is obtained by inverse transform. Time derivatives describing the fire front growth in time are then obtained by temporal limiting process.

Let $(x(s,t+\mathrm{d}t), y(s,t+\mathrm{d}t))$ be a point lying on new fire front at time $t+\mathrm{d}t$ which corresponds to a point $(x(s,t), y(s,t))$ lying on starting fire front at time t; s is a parameter. The information required at the point $(x(s,t), y(s,t))$ includes the orientation of the point in terms of component angle derivatives $x_s(s,t)$, $y_s(s,t)$, the direction of maximum fire propagation rate θ (the resultant wind-slope vector azimuth), and the shape of elliptical fire determined from the conditions local to that point in terms of dimensions $a(s,t)$, $b(s,t)$, $c(s,t)$. The Richards' equations for the time derivatives for the given point lying on the starting fire front then have the form [20]:

$$x_t(s,t) = \frac{a^2(s,t)C(x_s(s,t)S+y_s(s,t)C)-b^2(s,t)S(x_s(s,t)C-y_s(s,t)S)}{[b^2(s,t)(x_s(s,t)C-y_s(s,t)S)^2+a^2(s,t)(x_s(s,t)S+y_s(s,t)C)^2]^{1/2}} + c(s,t)S$$

$$y_t(s,t) = \frac{-a^2(s,t)S(x_s(s,t)S+y_s(s,t)C)-b^2(s,t)C(x_s(s,t)C-y_s(s,t)S)}{[b^2(s,t)(x_s(s,t)C-y_s(s,t)S)^2+a^2(s,t)(x_s(s,t)S+y_s(s,t)C)^2]^{1/2}} + c(s,t)C,$$

where $a(s,t)$, $b(s,t)$, and $c(s,t)$ is the length of the minor semi-axis (lateral from the center), the major semi-axis (forward from the center), and the distance forward of the ignition point to the center, respectively; $x_s(s,t)$, $y_s(s,t)$ determine the direction normal to the starting fire front, and C and S denote $\cos\theta$ and $\sin\theta$, respectively.

The coordinates of the corresponding point lying on the outer envelope of the set of ellipses which corresponds to the new fire front have the form [14]:

$$x(s,t+\mathrm{d}t) = x(s,t) + \mathrm{d}t c(s,t)S - \frac{a^2(s,t)b(s,t)b_s(s,t)(c_s(s,t)\mathrm{d}tS + x_s(s,t))\mathrm{d}t^2}{D(s,t)}$$

$$+\frac{\mathrm{d}t[Ca^2(s,t)A(s,t) - Sb^2(s,t)B(s,t)][D(s,t) - a^2(s,t)b_s^2(s,t)\mathrm{d}t^2]^{1/2}}{D(s,t)}$$

$$y(s,t+\mathrm{d}t) = y(s,t) + \mathrm{d}t c(s,t)C - \frac{a^2(s,t)b(s,t)b_s(s,t)(c_s(s,t)\mathrm{d}tC + y_s(s,t))\mathrm{d}t^2}{D(s,t)}$$

$$-\frac{\mathrm{d}t[Ca^2(s,t)A(s,t) + Sb^2(s,t)B(s,t)][D(s,t) - a^2(s,t)b_s^2(s,t)\mathrm{d}t^2]^{1/2}}{D(s,t)},$$

where

$$\begin{aligned} A(s,t) &= (Sx_s(s,t) + Cy_s(s,t) + c_s(s,t)\mathrm{d}t) \\ B(s,t) &= (Cx_s(s,t) - Sy_s(s,t)) \\ D(s,t) &= \left(a^2(s,t)A^2(s,t) + b^2(s,t)B^2(s,t)\right). \end{aligned}$$

Despite certain restrictions, the Richards' equations are of great significance for forest fire modelling and simulation.

Our alternative method [14, 15] allows us to derive the model directly using the knowlege of classical theory of envelopes of planar curves sets. This approach enables to better understand the elliptical fire propagation model and to derive the model also for other types of the local fire propagation observed during fire experiments. This approach also allows to derive explicit analytical formulae for new fire front represented by the envelope of the corresponding planar curves. Therefore, it has a good potential for the demonstration of fire propagation in various conditions and sensitivity of the models for selected input parameters.

2.1 Single Ellipse Case

In this paragraph, we demonstrate several cases of elliptical fire propagation for the case of single ellipse under homogeneous conditions and variable wind direction (see Figures 2 and 3).

In Figure 2, two steps of fire propagation are illustrated for the case of fire ignited in a point lying in the centre of coordinate system. *The first step* of fire propagation correspods to fire accelerated by wind blowing in the direction parallel to the y-axis. The shape of the fire front formed during the first step of fire propagation is a *single*

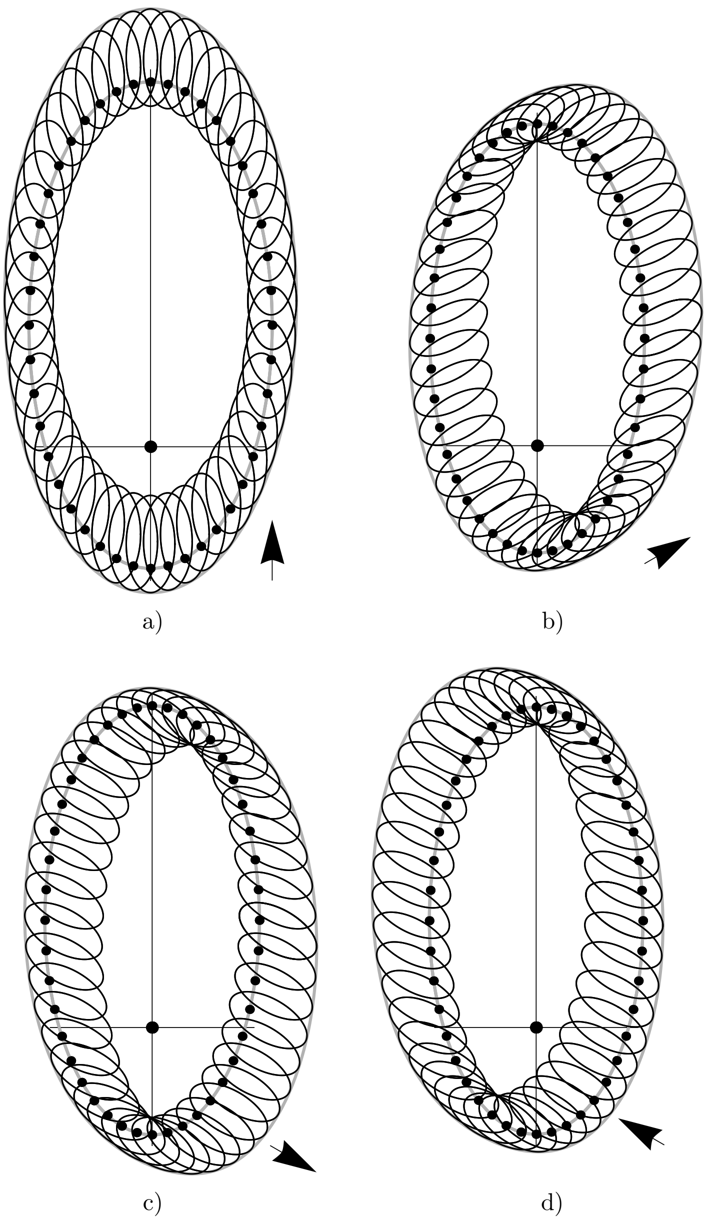

Fig. 2. Fire propagation under homogeneous conditions and variable wind direction: the case of single ellipse and simple shape of starting fire front

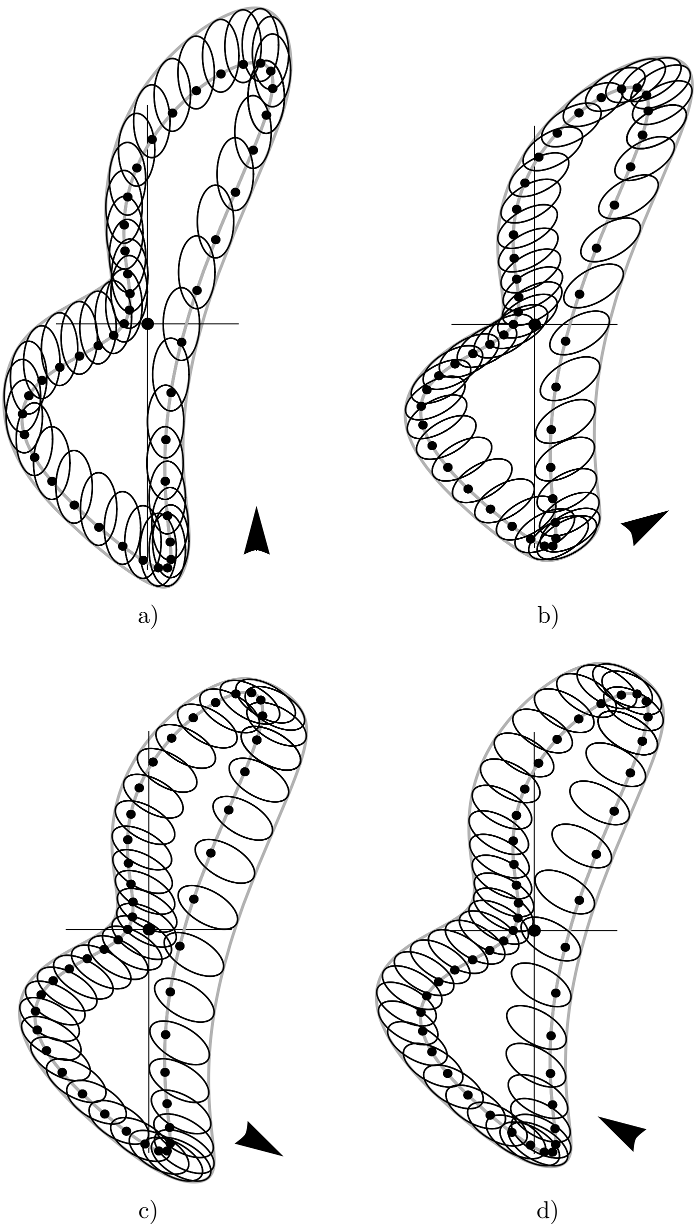

Fig. 3. Fire propagation under homogeneous conditions and variable wind direction: the case of single ellipse and more complex shape of starting fire front

ellipse having its major axis parallel to the y-axis (in the wind direction). The ratio of its major and minor axes lengths equals to 2:1 and its centre is shifted by about the length of its minor axis in regard of the centre of coordinate system. The resulting fire front is drawn in grey colour in Figures 2 a)–d).

The second step of fire propagation is represented by *starting fire front* (i.e., the resulting fire front which was formed in the previous step) and a set of 45 selected points lying at the starting fire front. According to Huygens' principle, these points act as ignition points of secondary local fires represented by a set of 45 secondary single ellipses. The major axes of these ellipses are parallel to the wind direction. The wind direction during the second step of fire propagation is highlighted in Figures 2 a)–d) by black arrows. In such a way, we represent the change of wind direction by about 0, $-\pi/3$, $-2\pi/3$ and $-5\pi/3$ in regard of the original wind direction (parallel to the y-axis) in Figure 2 a), Figure 2 b), Figure 2 c) and Figure 2 d), respectively. The corresponding outer envelopes of the sets of single ellipses, which form the resulting new fire fronts, are plotted in Figures 2 a)–d) using the explicit analytical formulae derived by our alternative method of the model derivation. The resulting *new fire fronts* are drawn in grey colour in Figures 2 a)–d).

Figure 3 illustrates fire propagation in homogeneous conditions and variable wind direction for the case of more difficult starting fire front shape. We assume that the fire front formed during *the first step* of fire propagation has a *"general" shape*. For its representation, we use a slightly modified, non-convex simple closed planar curve from [11]. The corresponding fire fronts are drawn in grey colour in Figures 3 a)–d).

The second step of fire propagation is represented by a set of 45 selected points lying on the *starting fire front* (formed during the previous step) corresponding to ignition sources of selected secondary local fires. These local fires are represented by a set of 45 secondary single ellipses. The values of wind direction change in Figures 3 a)–d) are the same as the ones in Figures 2 a)–d). The wind direction is again represented by black arrows and the resulting *new fire fronts* are drawn in grey colour.

2.2 Double Ellipse Case

In the following, several simple examples of elliptical fire propagation for the case of double ellipse under homogeneous conditions and variable wind direction will be given (see Figure 4 and Figure 5).

In Figure 4, we assume the case of a fire ignited in a point lying in the centre of the coordinate system. *The first step* of fire propagation correspods to fire accelerated by wind blowing in the direction parallel to the y-axis as before. The shape of resulting fire front after the first step of fire propagation is a *double ellipse* consisting of two half-ellipses having the same minor axes and the major axes parallel to the y-axis (in the wind direction). The ratios of the major and minor axes lengths of the first and the second half-ellipses equal to 2:1 and 1:1, respectively. The centres

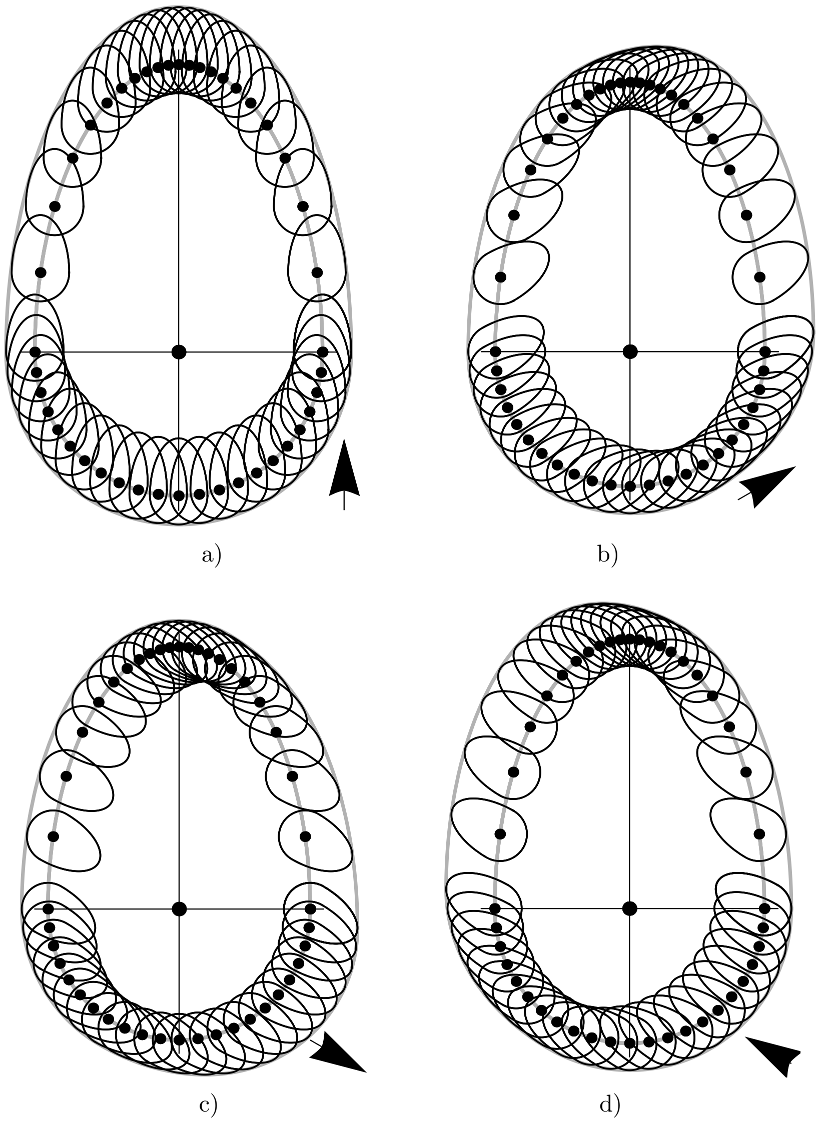

Fig. 4. Fire propagation under homogeneous conditions and variable wind direction: the case of double ellipse and simple shape of starting fire front

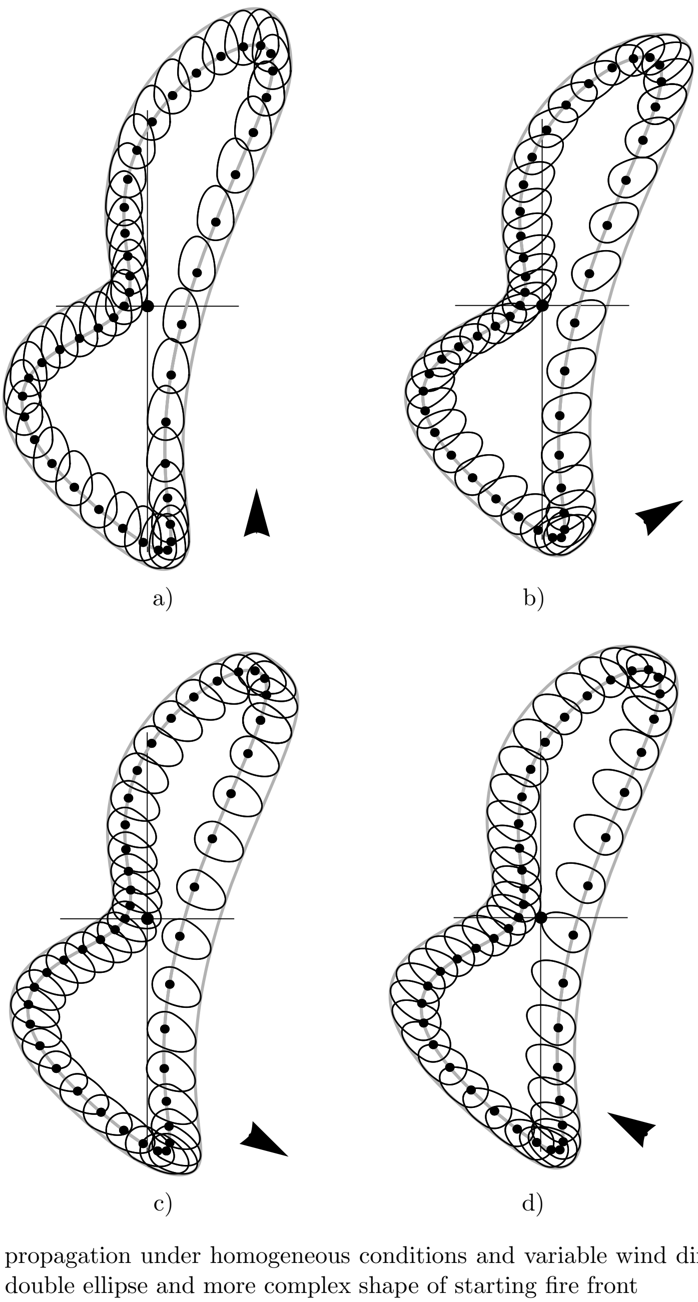

Fig. 5. Fire propagation under homogeneous conditions and variable wind direction: the case of double ellipse and more complex shape of starting fire front

of both half-ellipses lay in the centre of the coordinate system. The resulting fire fronts are drawn in grey colour in Figures 4 a)–d).

The second step of fire propagation is represented by the *starting fire front* (identical with the resulting fire front formed in the previous step) and a set of 45 selected points lying at the starting fire front. These points act as ignition points of secondary local fires represented by a set of 45 secondary double ellipses. The major axes of the double ellipses are parallel to the wind direction. The wind direction during the second step of fire propagation is highlighted by black arrows in Figures 4 a)–d). These arrows represent the wind direction change by about 0, $-\pi/3$, $-2\pi/3$ and $-5\pi/3$ in regard of the original wind direction (parallel to the y-axis) in Figure 4 a), Figure 4 b), Figure 4 c) and Figure 4 d), respectively. The corresponding outer envelopes of the set of double ellipses forming the resulting new fire fronts are plotted in Figures 4 a)–d) using the explicit analytical formulae derived by our method. The resulting *new fire fronts* are drawn in grey colour in Figures 4 a)–d).

Figure 5 shows fire propagation in homogeneous conditions and variable wind direction for the case of double ellipse and *"general" shape* of starting fire front. The corresponding *starting fire fronts* (formed during *the first step* of fire propagation), as well as the *new fire fronts* represented by envelopes of sets of selected double ellipses (formed during *the second step* of fire propagation) are drawn in grey colour in Figures 5 a)–d). The wind direction is represented by black arrows again. The number of ignition points lying on the starting fire front which generate secondary local fires represented by the set of secondary double ellipses is the same as in the previous case.

3 NON-ELLIPTICAL FIRE PROPAGATION

In the sequel, a non-elliptical fire propagation under homogeneous conditions and variable wind direction corresponding to the case of *tear shape* will be illustrated (see Figures 6 and 7).

In Figure 6, the case of fire ignited in a point lying in the centre of coordinate system is shown. *The first step* of fire propagation correspods to fire accelerated by wind blowing in the direction parallel to the y-axis. The shape of fire front formed during the first step of fire propagation is a *tear drop shape* having its major axis parallel to the y-axis (in the wind direction). The resulting fire fronts are drawn in grey colour in Figures 6 a)–d).

The second step of fire propagation is represented by *starting fire front* (identical with the resulting fire front formed in the previous step) and a set of 45 selected points lying at the starting fire front. These points act as ignition points of secondary local fires represented by a set of 45 curves of tear shape having the major axes parallel to the wind direction. The wind direction during the second step of fire propagation is highlighted by black arrows in Figures 6 a)–d) representing the wind direction change by about 0, $-\pi/3$, $-2\pi/3$ and $-5\pi/3$ in regard of the

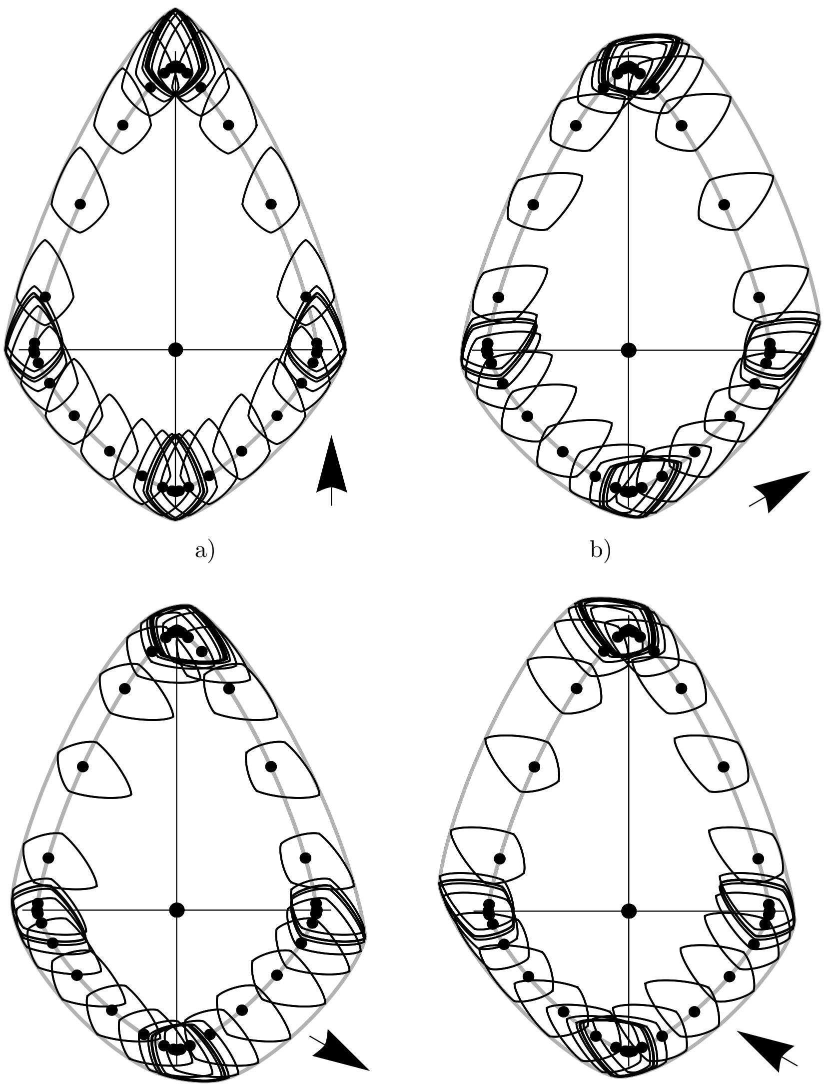

Fig. 6. Fire propagation under homogeneous conditions and variable wind direction: the case of tear shape and simple shape of starting fire front

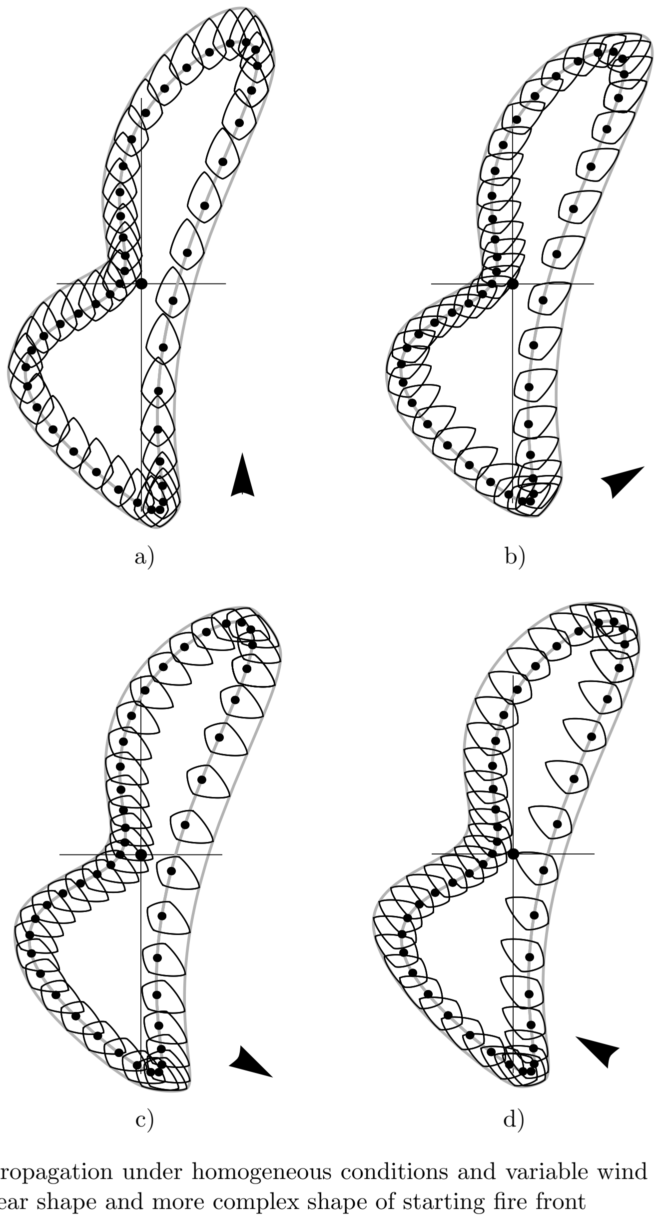

Fig. 7. Fire propagation under homogeneous conditions and variable wind direction: the case of tear shape and more complex shape of starting fire front

original wind direction (parallel to the y-axis) in Figure 6 a), Figure 6 b), Figure 6 c) and Figure 6 d), respectively. The corresponding outer envelopes of the sets of tear shaped curves, which form the resulting new fire fronts, are plotted in Figures 6 a)–d) by the use of the explicit analytical formulae derived by our method. The resulting *new fire fronts* are drawn in grey colour.

Figure 7 illustrates fire propagation in homogeneous conditions and variable wind direction for the case of tear and "complex" starting fire front shapes. The fire front shape formed during *the first step* of fire propagation is the same as in the previous paragraphs (*"general" shape*). The corresponding fire fronts are drawn in grey colour in Figures 7 a)–d).

To represent *the second step* of fire propagation, a set of 45 selected points lying on the *starting fire front* (identical with the resulting fire front formed during the first step) corresponding to ignition sources of selected local fires represented by a set of 45 tear shaped curves is shown. The wind direction change values in Figures 7 a)–d) are the same as the ones in previous figures. Again, the wind direction is represented by black arrows and the resulting *new fire fronts* are drawn in grey colour.

4 CONCLUSIONS

This paper deals with very actual problem of forest fire propagation modelling. Although the elliptical fire propagation model is more than 20 years old, only recently we derived its generalization for other local fire propagation shapes. This approach allows to derive the explicit analytical formulae describing the growth of forest fire front in space and time for selected cases of local fire propagation. We demonstrate three fire propagation models which correspond to three cases of mathematical representation of the local fire propagation, namely single ellipse, double ellipse and tear shaped curve. To illustrate the models, several simple examples of elliptical, as well as non-elliptical fire propagation under homogeneous conditions and variable wind direction are shown. The starting fire fronts in these examples were chosen to represent both very simple (single ellipse, double ellipse and tear shaped curve) and more complex (a non-convex simply closed planar curve) cases of fire shapes. The new fire fronts are represented by outer envelopes of the sets of single ellipses, double ellipses, and tear shaped curves. In spite of the fact that such forms of fire propagation were observed during laboratory and field fire experiments, until now it was not possible to present them because the explicit analytical formulae for the resulting fire front at given time derived by our approach were not available.

Acknowledgment

This work was partially supported by VEGA (project VEGA-2-0216-10) and ASFEU (project ITMS-26240220060) research agencies.

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