

## COMPUTER-AIDED DESIGN SYSTEMS

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### COMPUTER-AIDED DESIGN SYSTEM OF WIND TURBINE POWER PLANTS AERODYNAMICS CALCULATION

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**Abstract**—Main subject of study was system of aerodynamic numerical modeling of vertical-axis wind power rotors. Theoretical researching was analysis of methods to develop numerical scheme with help of Navier–Stokes equations for incompressible liquids. Shown description of existence methods and selected optimal method for numerical scheme developing. Developed numerical scheme for rotor aerodynamic solution.

**Index Terms**—Wind energy; combined wind turbines; software for aerodynamic calculation.

#### I. INTRODUCTION

The development of efficient wind turbines with vertical axis of rotation is important as they do not produce noise and are not influence on human health. But they need more complex development process as because of their form it's more difficult to calculate their efficiency. For that moment exist to main types of wind turbines: Savonius, Darrieus. Both of them work efficiently on different wind speeds. The Savonius turbines are drag-type devices, consisting of 2 or 3 blades and works due to the difference in forces on each blade. It's advantage that it easy to start rotation on low wind speed, but on high wind speed it can't give any additional energy. The Darrieus is a lift force type device, its blades have the form of wing placed vertically. The advantage of that wind turbine is great efficiency on great wind speeds, but it's difficult to start rotation on low speed. It is possible to develop combine wind turbine to obtain advantages of both types.

#### II. PROBLEM STATEMENT

Typical combined rotor consists of main Darrieus rotor and one or several accelerating Savonius that are placed on the same axis of rotation. When wind speeds are low, main torque is created by Savonius

rotor. When wind speeds are high rotation occurs due to Darrieus rotor. The task is to develop efficient placement of two rotor types to obtain efficient on different speeds of wind. To develop the combined wind turbine power plant with efficient rotation starting characteristics and efficient work on high wind speed it is necessary to use computation method because experimental method is too expensive and takes much time. It's necessary to use software for wind turbine aerodynamics computation [1]. To obtain the most accurate result it's necessary to use mathematical model that can closely describe real conditions. For that moment, Navier–Stokes equation is most closely describes the motion of viscous fluid substances.

#### III. NAVIER–STOKES EQUATION NUMERICAL CALCULATION

Because of nonlinearity of Navier stokes equation the solution can be obtain only numerically. As a method of numerical solution it is selected the finite volume method due to it's ability to user irregular grids of all shapes and effective approximation of curved boundaries.

Let us write the Navier–Stokes equation in partial derivatives

$$\begin{cases} \frac{\partial U_x}{\partial t} + \frac{\partial(U_x^2)}{\partial x} + \frac{\partial(U_x U_y)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left[ \ell_{eff} \left( 2 \frac{\partial U_x}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ \ell_{eff} \frac{\partial U_x}{\partial y} + \frac{\partial U_y}{\partial x} \right], \\ \frac{\partial U_y}{\partial t} + \frac{\partial(U_y U_x)}{\partial x} + \frac{\partial(U_y^2)}{\partial y} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left[ \ell_{eff} \left( \frac{\partial U_y}{\partial x} + \frac{\partial U_x}{\partial y} \right) \right] + \frac{\partial}{\partial y} \left[ \ell_{eff} \left( 2 \frac{\partial U_y}{\partial y} \right) \right], \\ \frac{\partial U_x}{\partial x} + \frac{\partial U_y}{\partial y} = 0, \end{cases} \quad (1)$$

where  $U_x, U_y$  are flow rates by coordinates  $x, y$  respectively;  $p$  is the pressure.

Finite volume method applies the method of subdomains for each equation (1) in a final volume ABCD.

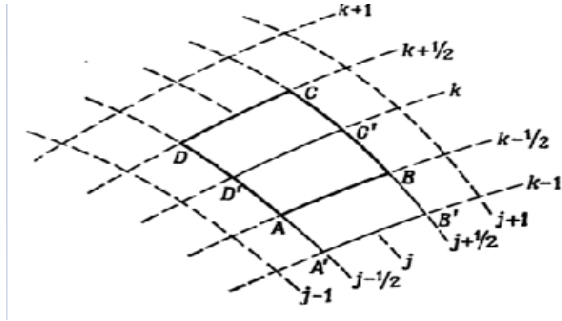


Fig. 1. The final volume of deformed grid

Let's make the following substitutions:

$$U_x = U, \quad U_y = V, \quad v_{\text{eff}} = k.$$

After that the following expression it is obtained:

$$\int_{\text{ABCD}} 1 \left( \frac{\partial U}{\partial t} + \frac{\partial(U^2)}{\partial x} + \frac{\partial(UV)}{\partial y} + \frac{\partial \rho}{\partial x} - \frac{\partial}{\partial x} \left[ k \left( 2 \frac{\partial U}{\partial x} \right) \right] - \frac{\partial}{\partial y} \left[ k \left( \frac{\partial U}{\partial y} + \frac{\partial V}{\partial x} \right) \right] \right) dx dy = 0, \quad (2)$$

$$\int_{\text{ABCD}} 1 \left( \frac{\partial V}{\partial t} + \frac{\partial(VU)}{\partial x} + \frac{\partial(V^2)}{\partial y} + \frac{\partial \rho}{\partial y} - \frac{\partial}{\partial x} \left[ k \left( \frac{\partial V}{\partial x} + \frac{\partial U}{\partial y} \right) \right] - \frac{\partial}{\partial y} \left[ k \left( \frac{\partial V}{\partial y} \right) \right] \right) dx dy = 0. \quad (3)$$

If we apply Green's theorem, the equation can be written as follows:

$$\frac{d}{dx} \int U dV + \int_{\text{ABCD}} H \cdot n ds = 0,$$

where  $H = (U, V)$ . In Cartesian coordinates we have:

$$H \cdot n ds = U^2 dy - UV dx + pd - 2k \frac{\partial U}{\partial x} dy + k \frac{\partial U}{\partial y} dx - kV.$$

The discrete form can be written as:

$$\frac{d}{dx} AU_{j,k} + \sum_{\text{AB}}^{\text{DA}} \left( U^2 \Delta y - UV \Delta x + p \Delta y - 2k \frac{\partial U}{\partial x} \Delta y + k \frac{\partial U}{\partial y} \Delta x - kV \right) = 0, \quad (4)$$

where  $A$  is the area of ABCD quadrangle, shown in Fig. 1;  $U_{j,k}$  is the average speed in the center of the quadrangle.

$$\Delta y_{\text{AB}} = y_B - y_A, \quad \Delta x_{\text{AB}} = x_B - x_A, \quad (5)$$

$$U_{\text{AB}} = \frac{U_{j,k-1} + U_{j,k}}{2}, \quad V_{\text{AB}} = \frac{V_{j,k-1} + V_{j,k}}{2}, \quad (6)$$

$$U_{\text{BC}} = \frac{U_{j+1,k} + U_{j,k}}{2}, \quad V_{\text{BC}} = \frac{V_{j+1,k} + V_{j,k}}{2}, \quad (7)$$

$$U_{\text{CD}} = \frac{U_{j,k+1} + U_{j,k}}{2}, \quad V_{\text{CD}} = \frac{V_{j,k+1} + V_{j,k}}{2}, \quad (8)$$

$$U_{\text{DA}} = \frac{U_{j-1,k} + U_{j,k}}{2}, \quad V_{\text{DA}} = \frac{V_{j-1,k} + V_{j,k}}{2}, \quad (9)$$

where  $j, k$  is the number of nodes on the computational grid by coordinates  $x$  and  $y$ , respectively.

For the sides AB derivatives:

$$\left[ \frac{\partial U}{\partial x} \right]_{j,k-1/2} = \frac{\Delta y_{\text{AB}} (U_{j,k-1} - U_{j,k}) + \Delta y_{k-1,k} (U_B - U_A)}{S_{\text{A'B'C'D'}}}, \quad (10)$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j,k-1/2} = \frac{-[\Delta x_{\text{AB}} (U_{j,k-1} - U_{j,k})] \Delta x_{k-1,k} (U_B - U_A)}{S_{\text{A'B'C'D'}}}, \quad (11)$$

where

$$S_{\text{A'B'C'D'}} = \Delta x_{\text{AB}} \Delta y_{k-1,k} - \Delta y_{\text{AB}} \Delta x_{k-1,k}.$$

Similarly, for the other side.

$$\left[ \frac{\partial U}{\partial x} \right]_{j+1/2,k} = \frac{\Delta y_{\text{BC}} (U_{j+1,k} - U_{j,k}) + \Delta y_{j,j+1} (U_C - U_B)}{\Delta x_{\text{BC}} \Delta y_{j,j+1} - \Delta y_{\text{BC}} \Delta x_{j,j+1}}, \quad (12)$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j+1/2,k} = \frac{-[\Delta x_{\text{BC}} (U_{j+1,k} - U_{j,k}) + \Delta x_{j,j+1} (U_C - U_B)]}{\Delta x_{\text{BC}} \Delta y_{j,j+1} - \Delta y_{\text{BC}} \Delta x_{j,j+1}}, \quad (13)$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j,k+1/2} = \frac{\Delta y_{\text{CD}} (U_{j-1,k+1} - U_{j-1,k}) + \Delta y_{k,k+1} (U_C - U_D)}{\Delta x_{\text{CD}} \Delta y_{k,k+1} - \Delta y_{\text{CD}} \Delta x_{k,k+1}}, \quad (14)$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j,k+1/2} = \frac{-[\Delta x_{CD}(U_{j+1,k+1} - U_{j-1,k}) + \Delta x_{k,k+1}(U_C - U_D)]}{\Delta x_{CD}\Delta y_{k,k+1} - \Delta y_{CD}\Delta x_{k,k+1}}, \quad (15)$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j+1/2,k} = \frac{\Delta y_{DA}(U_{j-1,k-1} - U_{j-1,k}) + \Delta y_{j-1,j}(U_D - U_A)}{\Delta x_{DA}\Delta y_{j-1,j} - \Delta y_{DA}\Delta x_{j-1,j}}, \quad (16)$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j-1/2,k} = \frac{-[\Delta x_{DA}(U_{j-1,k-1} - U_{j-1,k}) + \Delta x_{j+1,j}(U_D - U_A)]}{\Delta x_{DA}\Delta y_{j-1,j} - \Delta y_{DA}\Delta x_{j-1,j}}. \quad (17)$$

Considering the regularity of grid, i.e., its lines coincide with the lines of constant  $x$ ,  $y$  we have

$$\Delta y_{AB} = 0, \quad \Delta x_{BC} = 0, \quad \Delta y_{CD} = 0, \quad \Delta x_{DA} = 0,$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j,k-1/2} = \frac{U_B - U_A}{x_B - x_A},$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j,k-1/2} = \frac{U_{j,k-1} - U_{j,k}}{y_k - y_{k-1}},$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j-1/2,k} = \frac{U_{j-1,k} - U_{j,k}}{x_{j+1} - x_j},$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j+1/2,k} = \frac{U_C - U_B}{y_C - y_B}$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j,k+1/2} = \frac{U_C - U_D}{x_C - x_D},$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j,k+1/2} = \frac{U_{j-1,k+1} - U_{j-1,k}}{y_{k+1} - y_k},$$

$$\left[ \frac{\partial U}{\partial x} \right]_{j-1/2,k} = \frac{U_{j-1,k-1} - U_{j-1,k}}{x_j - x_{j-1}},$$

$$\left[ \frac{\partial U}{\partial y} \right]_{j-1/2,k} = \frac{U_D - U_A}{y_D - x_A}.$$

Similar expressions for  $V$  and substituting the expression (5) – (17) into (4) we obtain the following equation:

$$\begin{aligned} & \frac{d}{dx} AU_{j,k} + 0,25(U_{j,k-1} + U_{j,k})(V_{j,k-1} + V_{j,k})(x_B - x_A) + k \frac{U_{j,k-1} + U_{j,k}}{y_k - y_{k-1}}(x_B - x_A) \\ & - 0,5k(V_{j,k-1} + V_{j,k}) + 0,25(U_{j,k-1} + U_{j,k})^2(y_C - y_B) + 0,5(p_{j+1,k} + p_{j,k})(y_C - y_B) \\ & + 2k \frac{U_{j+1,k} - U_{j,k}}{x_{j+1} - x_j}(y_C - y_B) - 0,5k(V_{j+1,k} + V_{j,k}) + 0,25(U_{j,k+1} - U_{j,k})(V_{j,k+1} + V_{j,k})(x_C - x_D) \\ & + k \frac{U_{j-1,k+1} - U_{j-1,k}}{y_{k+1} - y_k}(x_C - x_D) - 0,5k(V_{j+1,k} + V_{j,k}) + 0,25(U_{j-1,k} + U_{j,k})^2(y_D - y_A) \\ & + 0,5(p_{j-1,k} + p_{j,k})(y_D - y_A) - 2k \frac{U_{j-1,k-1} - U_{j-1,k}}{x_j - x_{j-1}}(y_D - y_A) - 0,5k(V_{j-1,k} + V_{j,k}) = 0, \end{aligned} \quad (21)$$

$$\begin{aligned} & \frac{d}{dx} AV_{j,k} + 0,25(V_{j,k-1} + V_{j,k})^2(x_B - x_A) + 0,5(p_{j,k-1} - p_{j,k})(x_B - x_A) + 2k \frac{V_{j+1,k} - V_{j,k}}{y_k - y_{k-1}}(x_B - x_A) \\ & - 0,5k(U_{j,k-1} + U_{j,k}) + 0,25(V_{j+1,k} + V_{j,k})(U_{j+1,k} + U_{j,k})(y_C - y_B) - k \frac{V_{j+1,k} - V_{j,k}}{x_{j+1} - x_j}(y_C - y_B) \\ & - 0,5k(V_{j+1,k} + V_{j,k}) + 0,25(V_{j,k+1} + V_{j,k})^2(x_C - x_D) + 0,5(p_{j,k+1} + p_{j,k})(x_C - x_D) \\ & + 2k \frac{V_{j-1,k+1} - V_{j-1,k}}{y_{k+1} - y_k}(x_C - x_D) - 0,5k(U_{j,k+1} + U_{j,k}) + 0,25(V_{j-1,k} + V_{j,k}) \\ & \cdot (U_{j-1,k} + U_{j,k})(y_D - y_A) + k \frac{V_{j-1,k} - V_{j,k}}{x_j - x_{j-1}}(y_D - y_A) - 0,5k(U_{j-1,k} + U_{j,k}) = 0. \end{aligned} \quad (22)$$

$$\frac{U_{j+1,k} - U_{j-1,k}}{2\Delta x} + \frac{V_{j,k+1} - V_{j,k-1}}{2\Delta y} = 0. \quad (23)$$

We obtain equations system of the form

$$bU + nV = mP, \quad (24)$$

where  $b, n, m$  is the matrix coefficients before unknown  $U, V, P$ .

First, we solve the system with respect to velocities, and then refine the speed, solving the system of relative pressure.

The solution of equations with respect to velocities can be produced separately by coordinates.

1) Solve the system, taking into account that velocities along the axis  $y$  ( $V$ ) – constants ( $V = \text{const}$ ).

2) Solve the system, taking into account that velocities along the axis  $x$  ( $U$ ) – constants ( $U = \text{const}$ ).

#### IV. DEVELOPMENT OF COMBINED WIND TURBINE AND CALCULATION OF POWER COEFFICIENT

As numerical calculation of Navier–Stokes equation is quite difficult to implement programmatically, it is necessary to use software that is already implemented, optimized and verified. The software market has lot's of propositions Warlock, Flow Vision and so one, but in current calculation Ansys software package will be used, as it gives one of the most accurate results for that moment [2].

To investigate optimal wind turbine configuration were chosen two combined wind turbines and Savonius with Darrier to compare output power coefficient (Fig. 2).

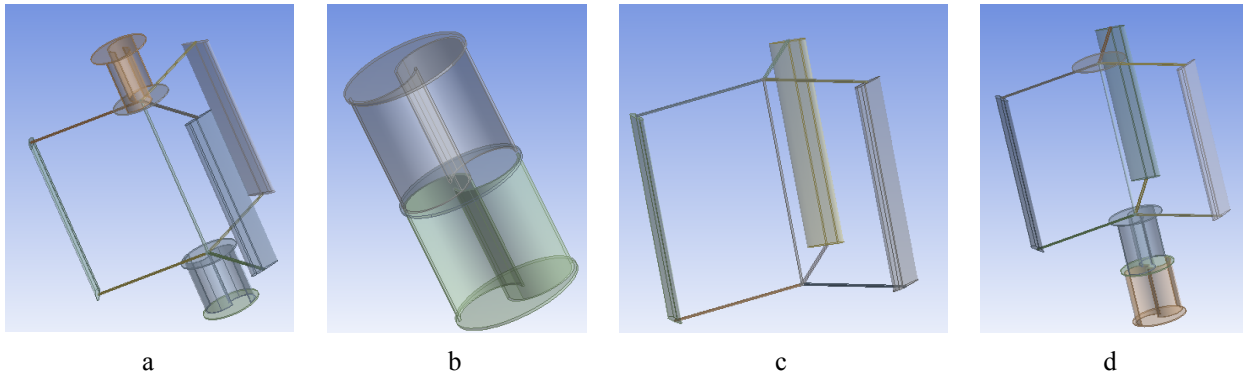


Fig. 2. Combined wind turbines: (a) combined SDS; (b) Savonius; (c) Darrier; (d) combined DSS

The power coefficient is calculated on the following conditions:

- density of air:  $1.225 \text{ kg/m}^3$ ;
- angular velocity of turbine rotation:  $18.85 \text{ rad/s}$ ;
- diameter and height of single Darrier wind turbine:  $1.5 \text{ m}$  and  $1.9 \text{ m}$ ;
- diameter and height of single Savonius wind turbine:  $0.5 \text{ m}$  and  $0.4 \text{ m}$ .

And it was obtained the following result for wind speeds  $4\text{--}9 \text{ m/s}$ . (Fig. 3).

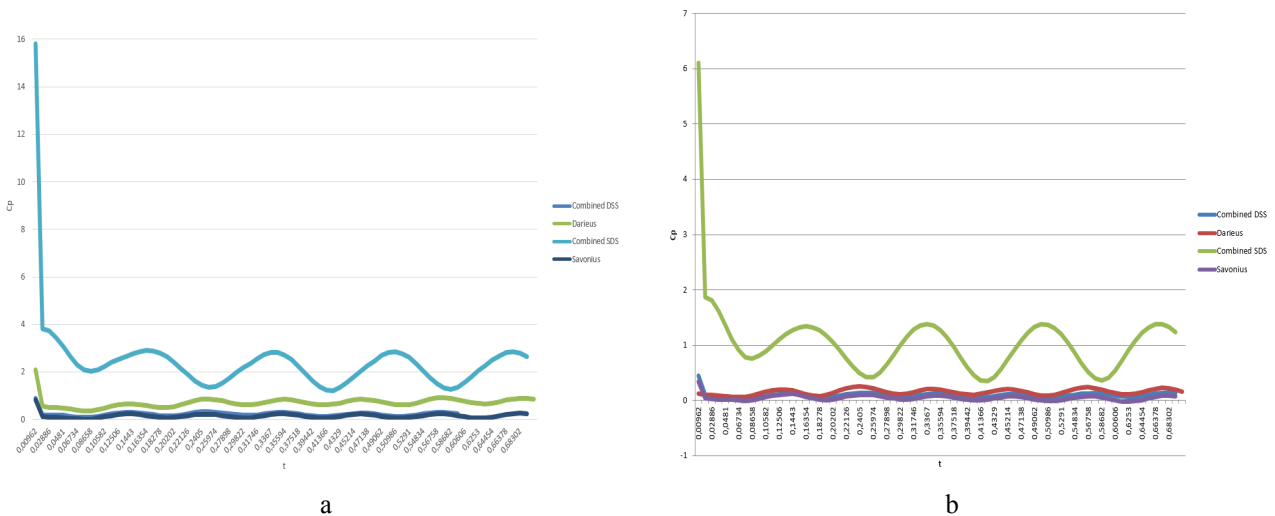


Fig. 3. Dependency of power coefficient  $C_p$  from time at wind speed: (a) for  $4 \text{ m/s}$ ; (b) for  $5 \text{ m/s}$ ; (c) for  $6 \text{ m/s}$ ; (d) for  $7 \text{ m/s}$ ; (e) for  $8 \text{ m/s}$ ; (f) for  $10 \text{ m/s}$

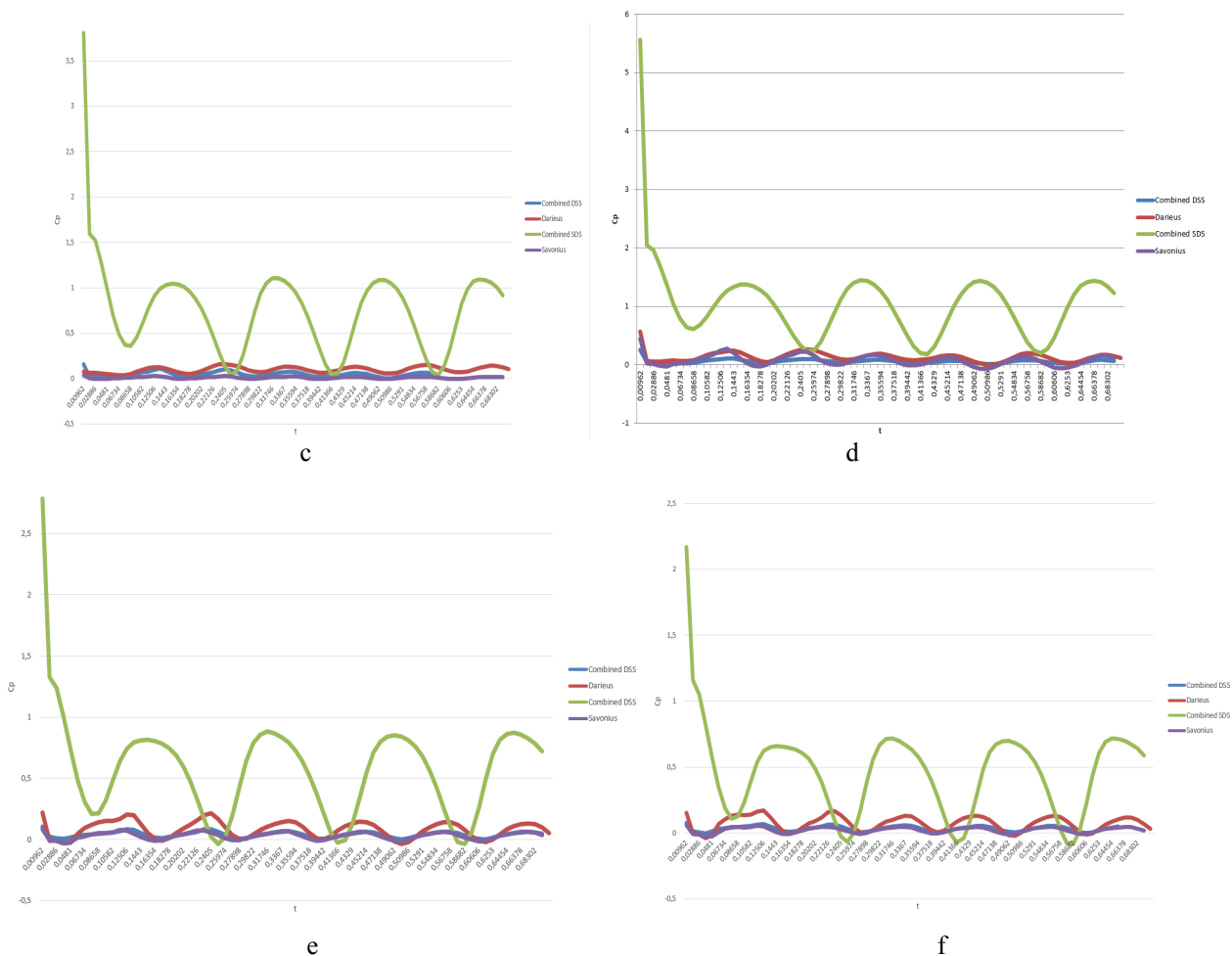


Fig. 3. Ending. (See also p. 59)

## V. CONCLUSION

According to obtained result it can be concluded that for Combined wind turbine of DSS type two Savonius turbines on the bottom working as brakes for each other and don't let to occur starting momentum for Darrius wind turbine.

On the other hand combined wind turbine of SDS type obtained the opportunity to get starting moment for Darrius. However with the increase of wind speed the power coefficient is starting to decrease

because of two Savonius wind turbines that resist to the ram flow.

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**В. М. Синеглазов, Ш. А. Хок. Автоматизована система аеродинамічного розрахунку роторів вітроенергетичних установок**

Розглянуто методи аналізу чисельного аеродинамічного моделювання вертикально-осьових вітроенергетичних установок. Рівняння Нав'є–Стокса було обрано як метод обрахування характеристик. Обрано оптимальну модель для чисельного аналізу.

**Ключові слова:** рівняння Нав'є–Стокса; вертикально-осьові вітроенергетичні установки; програмні методи розрахунку аеродинамічних характеристик.

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**В. М. Синеглазов, Ш. А. Хок. Автоматизированная система аэродинамического расчета роторов ветроэнергетических установок**

Рассмотрены методы анализа численного аэродинамического моделирования вертикально-осевых ветроэнергетических установок. Уравнение Навье–Стокса было выбрано как метод вычисления характеристик. Выбрана оптимальная модель для численного анализа.

**Ключевые слова:** уравнение Навье–Стокса; вертикально-осевые ветроэнергетические установки; программные методы расчета аэродинамических характеристик.

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