Study of Alfvénic vortex shedding past a cylindrical obstacle

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Introduction

Over a wide range of Reynolds numbers, fluid flow around a bluff obstacle, such as a circular cylinder, may lead to the creation of a chain of vortices (Kármán vortex street) that form just behind the obstacle and disconnect from it periodically and alternately from each side. This periodic vortex formation is called vortex shedding [1].

This phenomenon has been widely studied in hydrodynamic conditions, but is less well understood in magnetohydrodynamic (MHD) conditions [2]. It has been investigated by a number of numerical simulations in magnetic field environments, mainly in two dimensions – e.g. [2, 3, 4].

Observations suggest the possibility of its occurrence in the Sun's atmosphere [5]. For example, radial and azimuthal oscillations that may be related to self-oscillating processes such as vortex shedding have been observed in coronal mass ejections [6]. It is also a possible mechanism for excitation of kink mode oscillations in coronal loops [7].

Numerical model

The phenomenon of vortex shedding around a circular cylindrical obstacle was studied numerically in MHD conditions in three spatial dimensions using the numerical code Lare3d. A parametric study was performed for different values of magnetic field (0, 5, 10 and 15 G) perpendicular to the plasma flow plane and the same initial flow velocity and obstacle size.

This model mimics coronal mass ejection flowing around a coronal loop and leading to vortex shedding, which is known as a probable mechanism for excitation of kink-mode oscillations in coronal loops [7].

Numerical simulations were performed using the simulation box shown in the illustration (Figure 1). Each simulation lasted t = 1000 in time units corresponding to about 1.12 s.

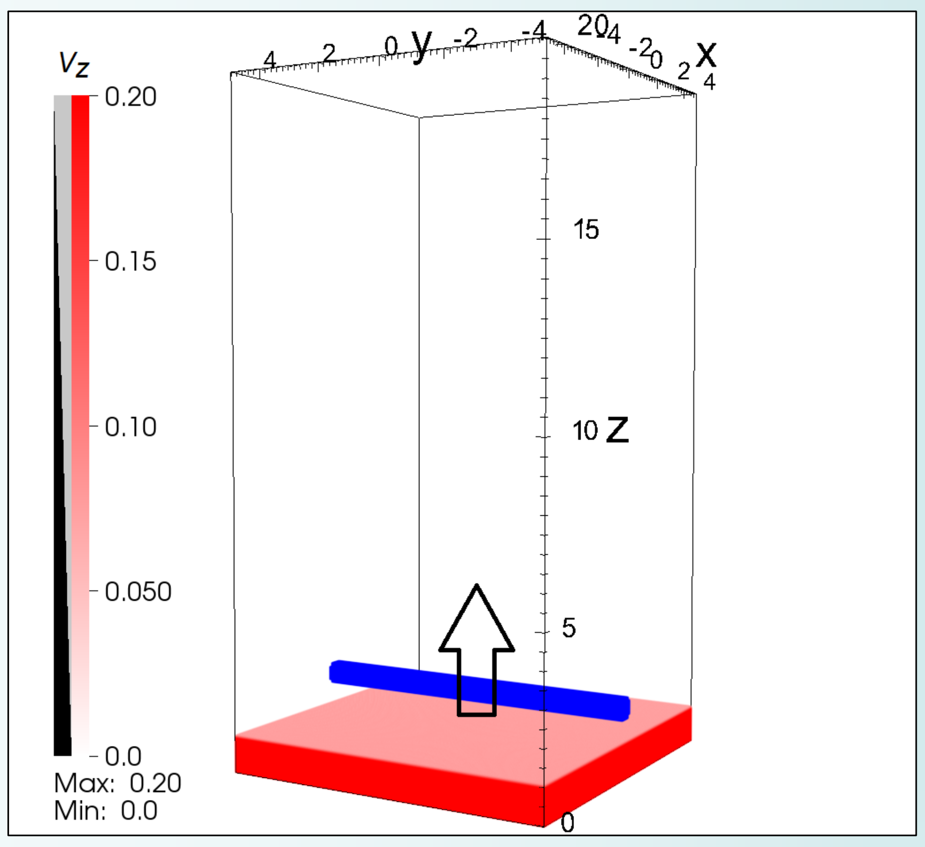

Figure 1: Illustration of velocity v_z distribution at the time $t = 2$ (2.24 s) The arrow indicates the initiate flow velocity $v_0 = 0.2$ (0.178 Mm · s^{-1}). The obstacle of the size $r = 0.316$ (0.316 Mm) is represented in blue.

The gravitational field was not considered and the ideal MHD equations were used:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0, \quad (1)$$

$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \nabla)\mathbf{v} + \nabla p - \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} = 0, \quad (2)$$

$$\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{v} = 0, \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \qquad \nabla \cdot \mathbf{B} = 0, \quad (4)$$

where ρ is the fluid density, $\mathbf{v}$ is the flow rate, p is the gas pressure, $\mathbf{B}$ is the magnetic induction, μ_0 is the vacuum permeability and γ is the heat capacity ratio.

Results

Figures 2 and 3 present the density distribution at three timesteps in non-magnetic field environment and in the strongest magnetic field to copmare the time evolution of the vortex shedding process in both cases. Figure 4 presents the density distribution in all the simulations at the last timestep to compare the structure of the developped drag. Finally, Figure 5 presents the time evolution of the relative density change in all the simulations which enables to analyze the period of this proces using wavelet analysis [8].

Time evoution of density - environment without magnetic field

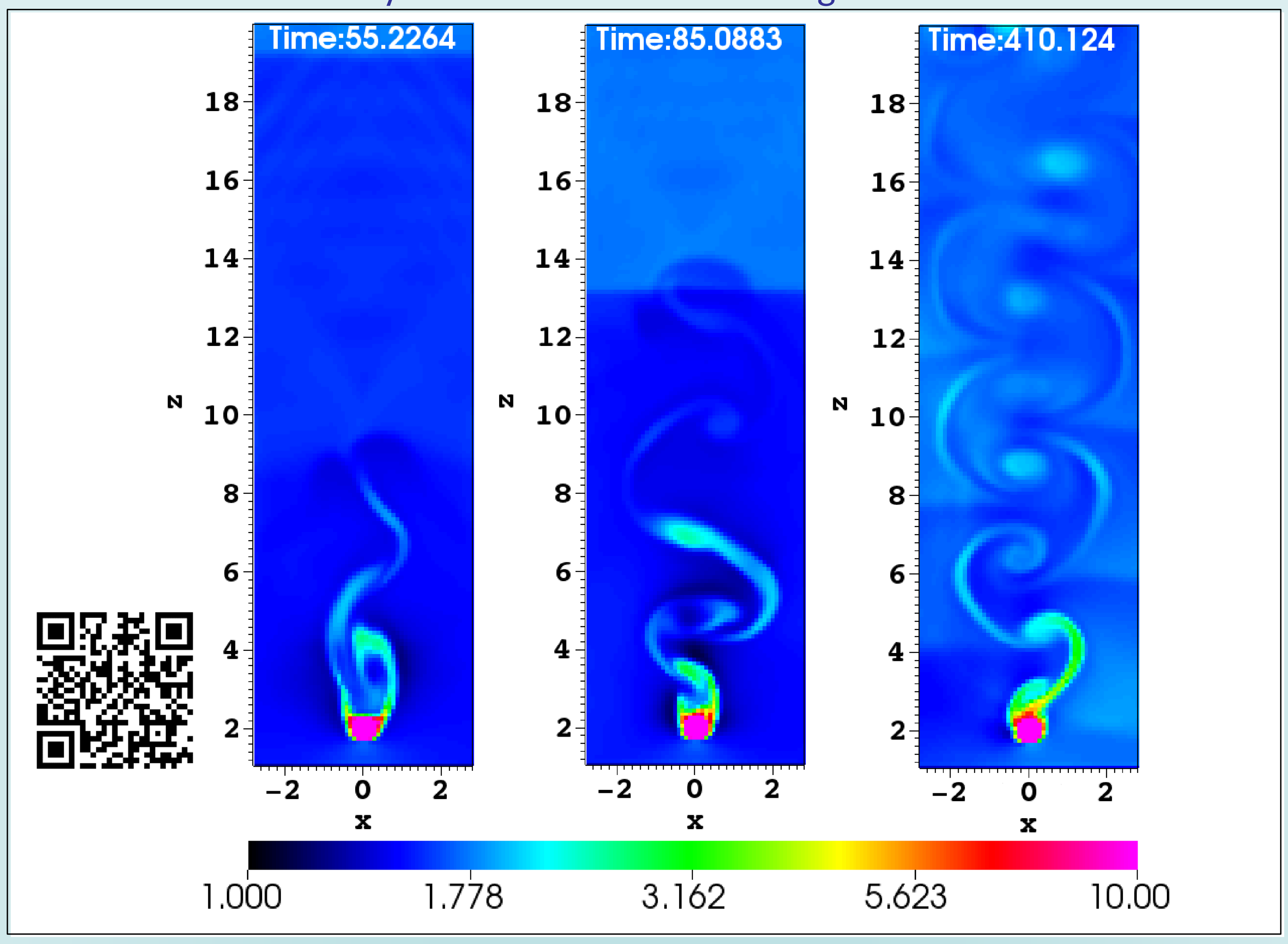

Figure 2: Density time evolution in non-magnetic field envirnonment, measured in the units of 10^{-12} kg · m^{-3}. The time is displayed in the units of 1.12 s. The legend is relevant for all the other pseudocolor plots. The whole simulation can be viewed online in the video referenced by the QR code.

Time evolution of density - environment with magnetic field 15 G

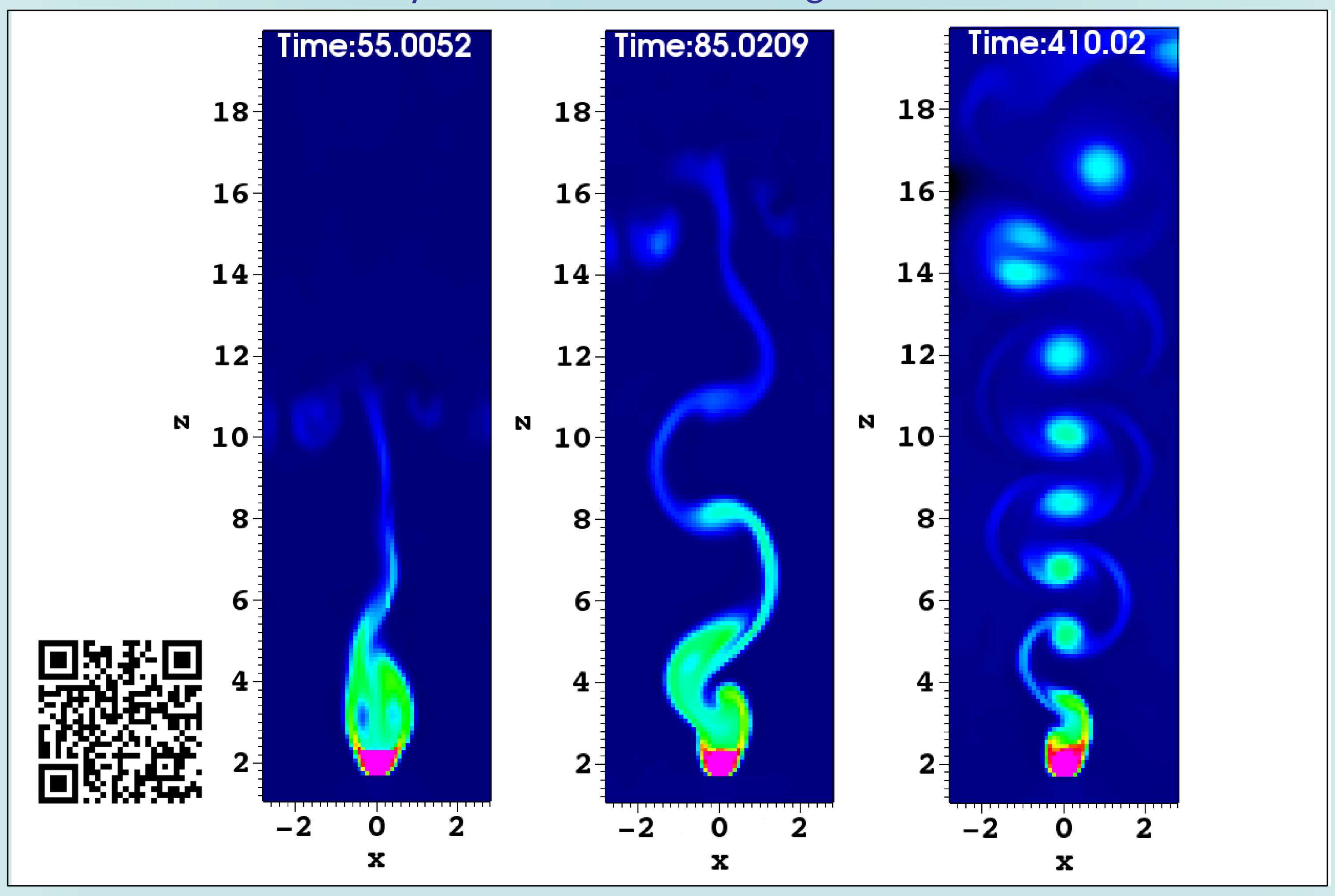

Figure 3: Density time evolution in magnetic field B_y = 15 G, measured in the units of 10^{-12} kg · m^{-3}. The time is displayed in the units of 1.12 s. The whole simulation can be viewed online in the video referenced by the QR code.

Density distribution – comparation

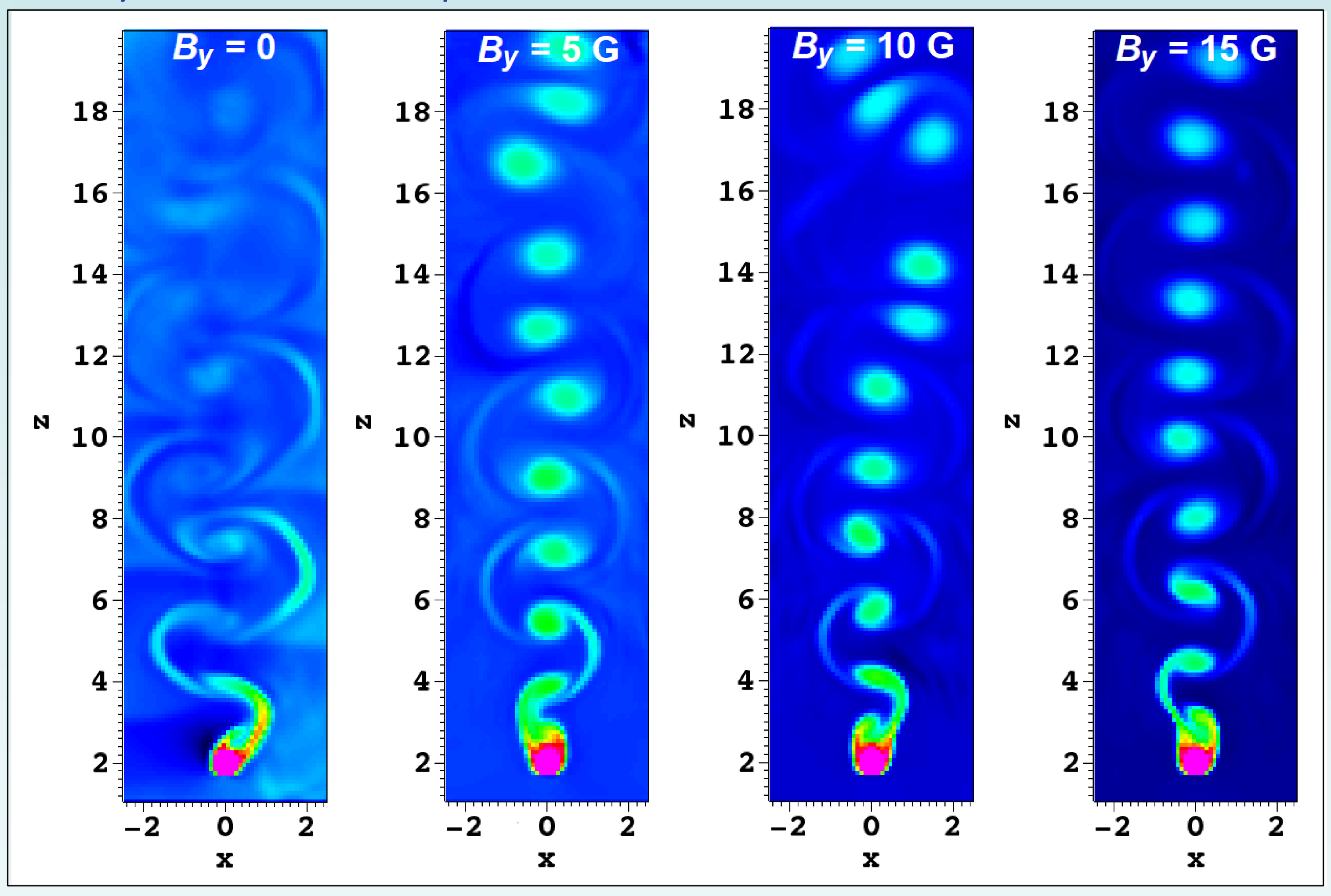

Figure 4: Density distribution at the last timestep 1000 (1120 s) for all the values of B_y, measured in the units of 10^{-12} kg · m^{-3}.

Conclusion

The process of vortex shedding and the structure of Kármán vortex street has been studied numerically in hydrodynamic environment and three different MHD environments. The simulations show that in the MHD case denser vortices are created. It is also evident that the presence of magnetic field perpendicular to the flow plane makes the vortex shedding frequency increase and causes higher periodical density changes. In the future we intend to use stronger magnetic field inside the obstacle and extend the problem on gravitational field to approximate it more to the solar corona.

Relative density change – comparation

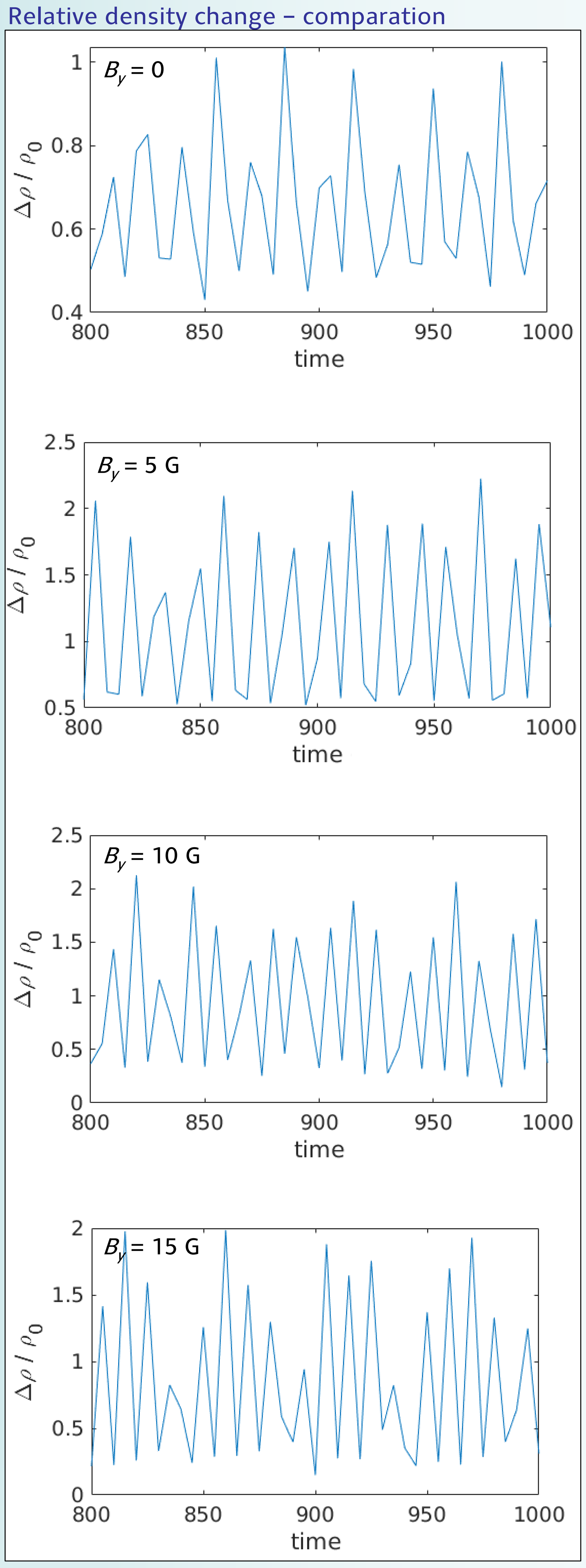

Figure 5: Time evolution of relative density change at the point $x = 0$, $y = 0$, $z = 5$ Mm for all the values of B_y. The time is displayed in the units of 1.12 s.

B_y	0	5 G	10 G	15 G
P	12.701	10.830	9.428	8.736

Table 1: Values of vortex shedding period obtained from the time evolution of relative density change using wavelet analysis [8], in the units of 1.12 s.

Acknowledgement

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