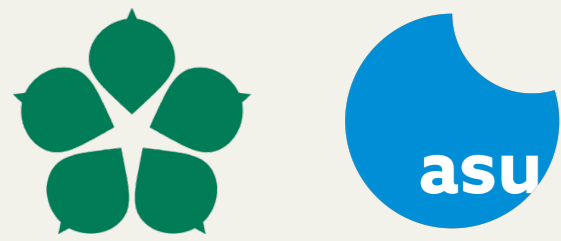


# Collective and individual oscillations of prominence threads excited by vortex shedding



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## Introduction

Solar prominences are large bright cloud-like features that extend to more than 50 Mm above the solar surface, composed of multiple threads, which are subject to oscillations. According to Nakariakov et al. (2009), in some cases, the excitation of kink-mode (the simplest case of transverse) horizontally polarised oscillations in these structures can be explained by the model they present, in which coronal mass ejections cause the vortex shedding (VS) phenomenon, which leads to the oscillations. VS is well known in hydrodynamic conditions and consists in a periodic alternate formation of vortices from each of the two sides of a blunt flow obstacle, which can form a pattern of vortices, called Kármán vortex street (KVS). We present a numerical study of transverse oscillations in solar prominence threads in association with VS that follows on from our previous study Jelínek et al. (2022), which supports the suggestion that VS might excite such oscillations in prominence threads.

## Numerical model

- Ideal magnetohydrodynamic equations in 3D
- Lare3d code
- 360 (432) × 360 × 1200 grid points → high-performance computing was needed
- No gravitational field
- Only the  $y$ -component of initial magnetic field
- Single and multiple flexible cylindrical structures (Cases #1 to #4) with radius square  $r^2 = 0.1 \text{ Mm}^2$ , fixed at boundaries, representing prominence threads
  - Case #2: different initial distances between the centres of the cylinders ( $2r$ ,  $3r$  and  $6r$ , where  $r$  is the radius of a cylinder)
- Plasma bulk motion from the lower face of the box constantly throughout the simulations (this motion is relative → can be treated as the motion of the magnetic structure in a stationary plasma environment)
  - Velocity corresponds to lower velocity values of coronal mass ejections

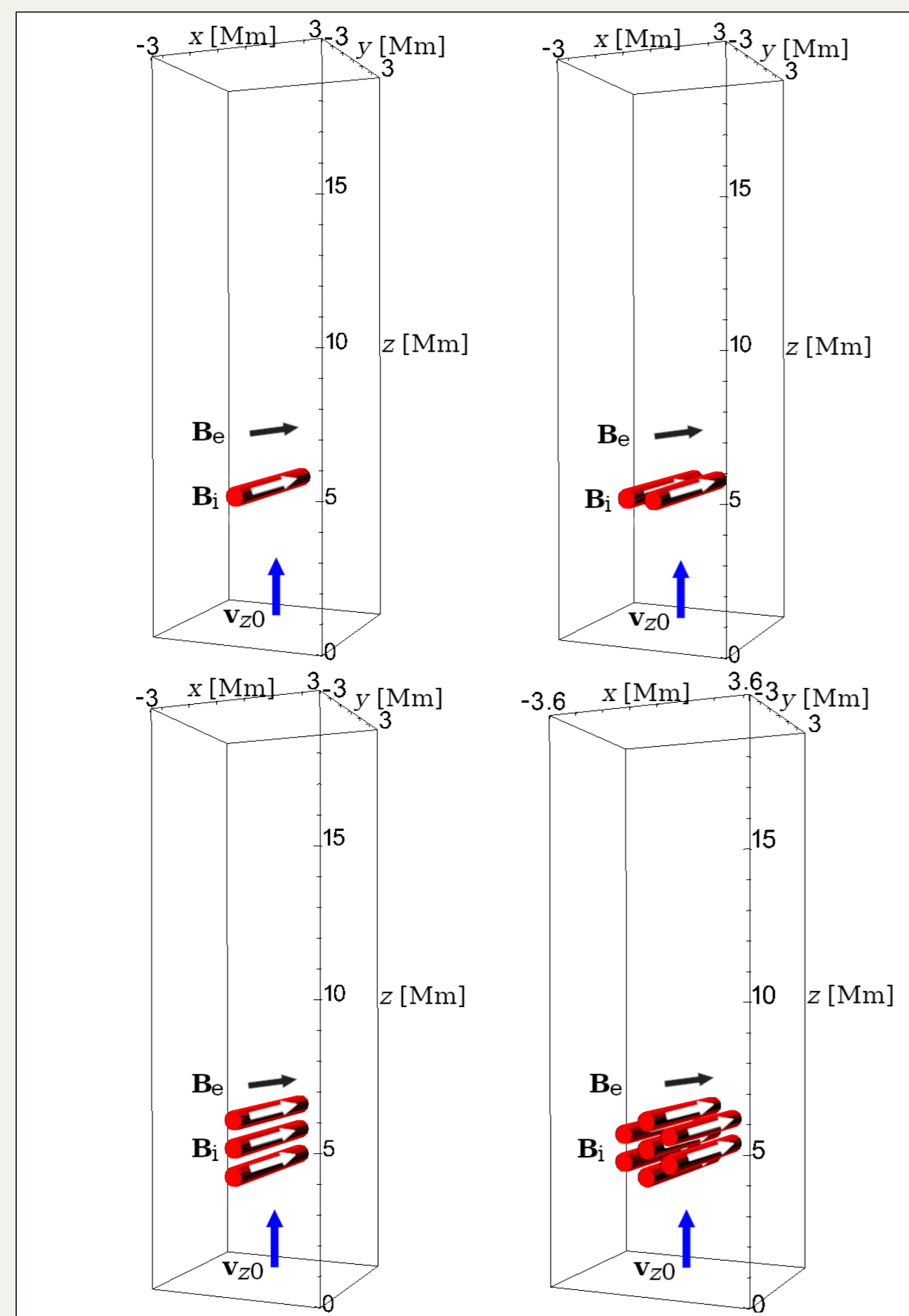


Figure 1. The sketches of the simulation boxes of Cases #1 to #4 respectively including the obstacles located. The constant flow is denoted as  $v_{z0}$ .

Table 1: Initial physical parameters of the studied cases – velocity of the source of flow ( $v_{z0}$ ), external and cylinder mass densities ( $\rho_e$ ,  $\rho_c$ ), external and cylinder temperatures ( $T_e$ ,  $T_c$ ), external and cylinder magnetic fields ( $B_e$ ,  $B_c$ ).

$v_{z0}$ [m s <sup>-1</sup> ]	$\rho_e$ [kg m <sup>-3</sup> ]	$\rho_c$ [kg m <sup>-3</sup> ]	$T_e$ [K]	$T_c$ [K]	$B_e$ [T]	$B_c$ [T]
$1.78 \cdot 10^5$	$10^{-12}$	$50 \cdot 10^{-12}$	$2 \cdot 10^6$	$6 \cdot 10^3$	$10^{-3}$	$1.03 \cdot 10^{-3}$

## Results

- Cases #1 and #3: the cylinders exhibit initial vertically polarised oscillations
- Cases #2 and #4, i.e. when horizontal structure is present: same, but the density-weighted centres oscillate with both  $z$ - (vertical) and  $x$ - (horizontal) components (except the middle cylinders of Case #4)

## Case #2 – 2r, 3r and 6r: mass density distribution

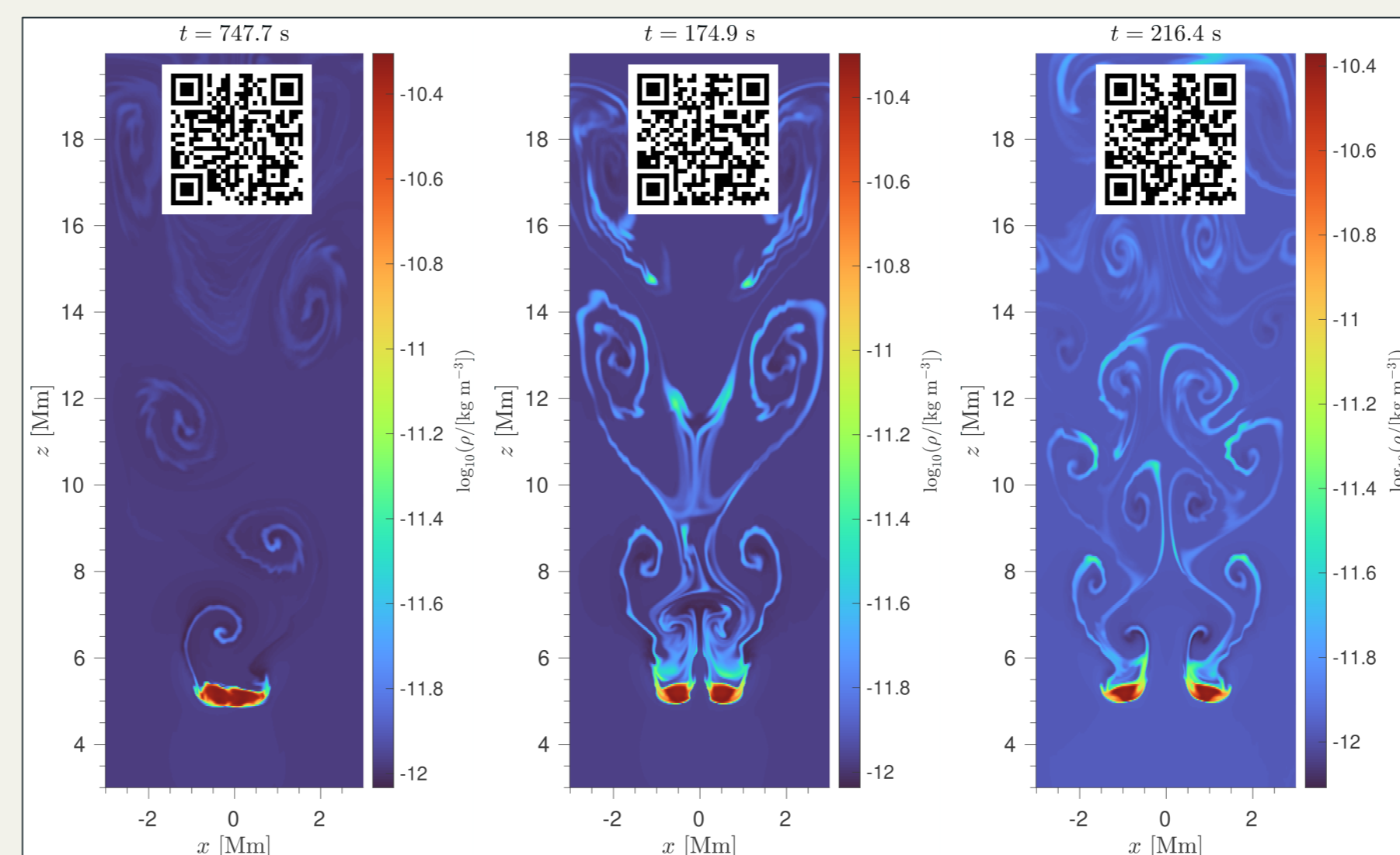


Figure 2. Mass density distribution in Case #2 at configurations  $2r$ ,  $3r$  and  $6r$  respectively at  $y = 0$  at indicated times. In all panels, VS taking place is captured – see videos available at the QR codes. In the left panel, a KVS is captured. In the middle panel, two halves of KVSs are captured. In the right panel, two opposite KVSs are captured.

## Cases #1, #3 and #4: mass density distribution

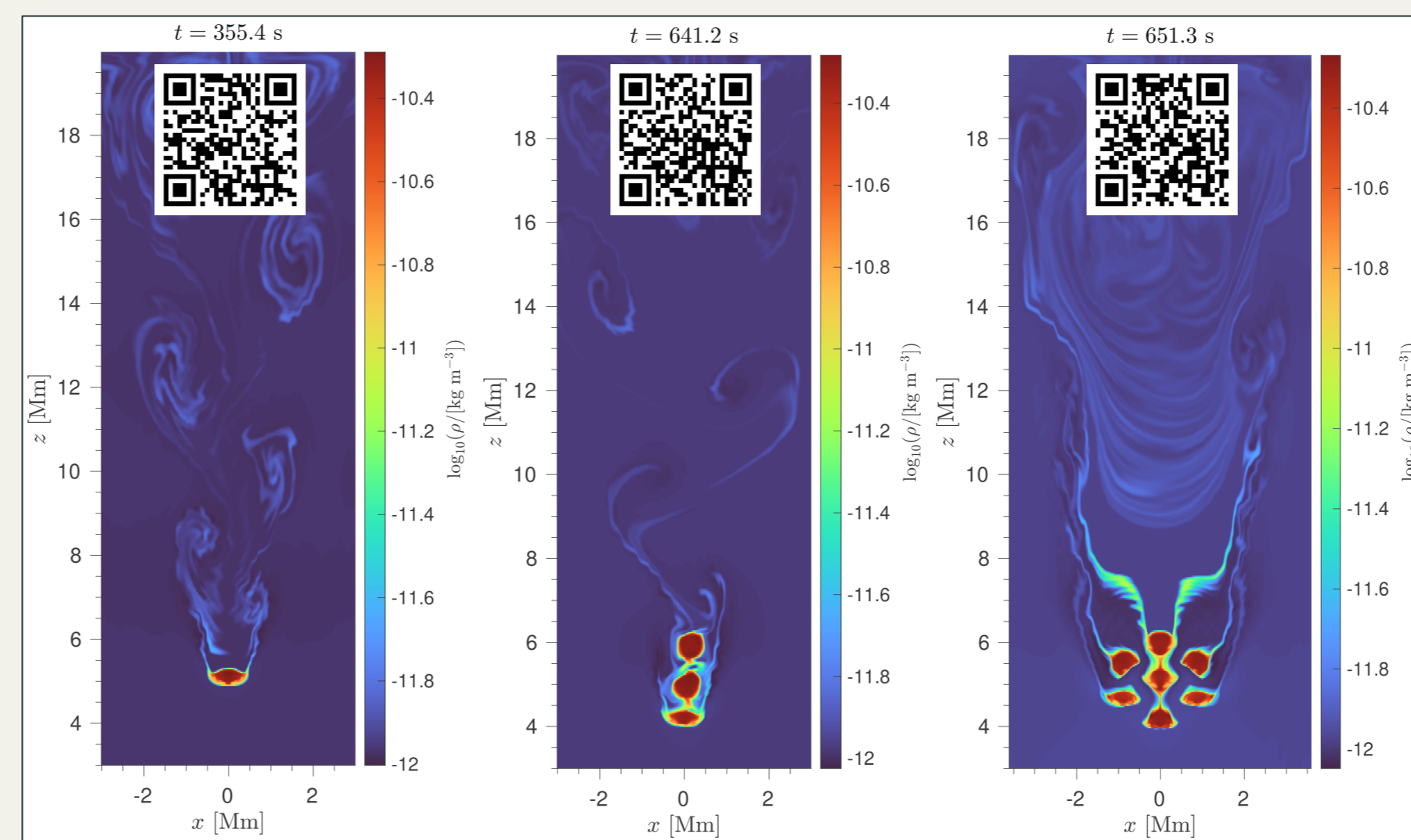


Figure 3. Mass density distribution at Cases #1, #3 and #4 respectively at  $y = 0$  at indicated times. In the left and middle panel, VS taking place and a KVS is captured – see videos available at the QR codes.

## Case #3 – position evolution analysis

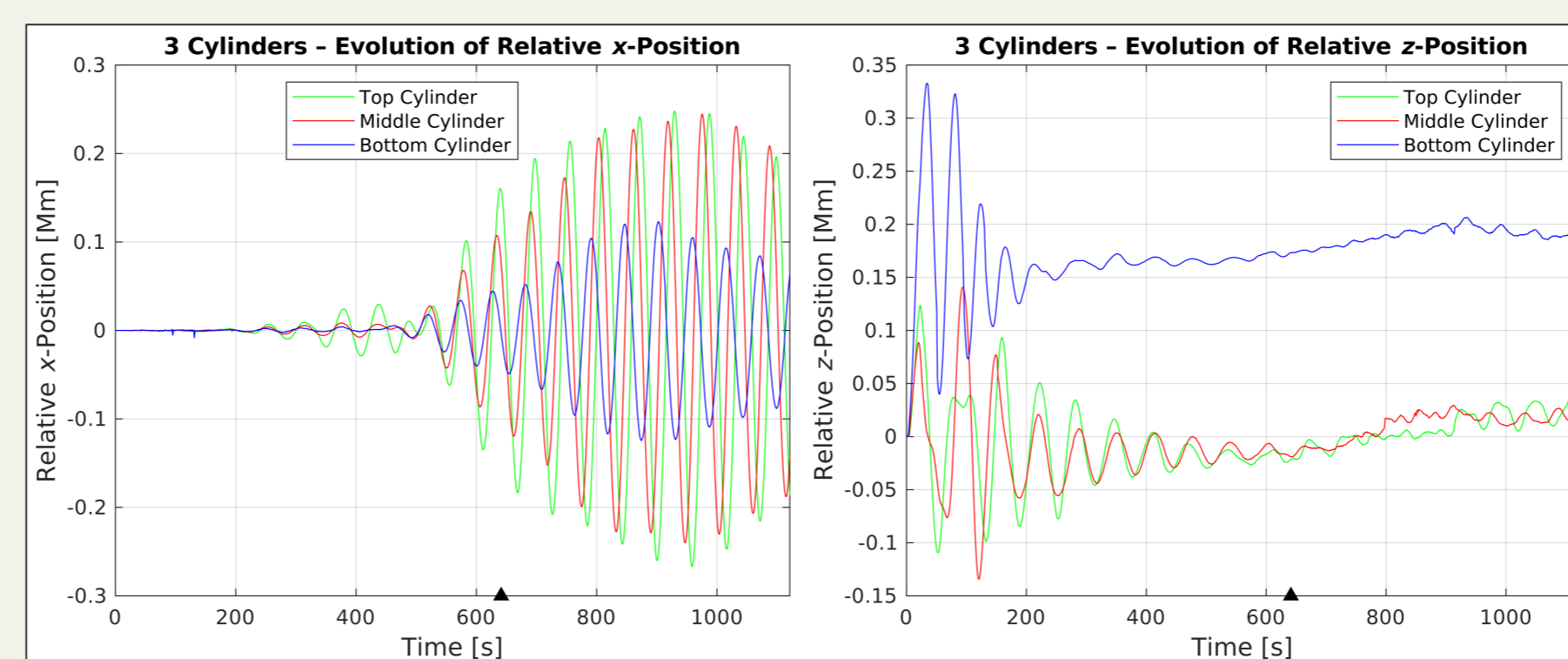


Figure 4. Left: evolution of approximate relative  $x$ -position; right: evolution of approximate relative  $z$ -position, i.e. displacement from initial positions, for Case #3, calculated by locating the density-weighted centre of the area identified as the transverse cross-section of the cylinder at  $y = 0$ . The mark indicates the time to which the relating mass density colormap (Fig. 3, middle) corresponds.

## Case #4 – position evolution analysis

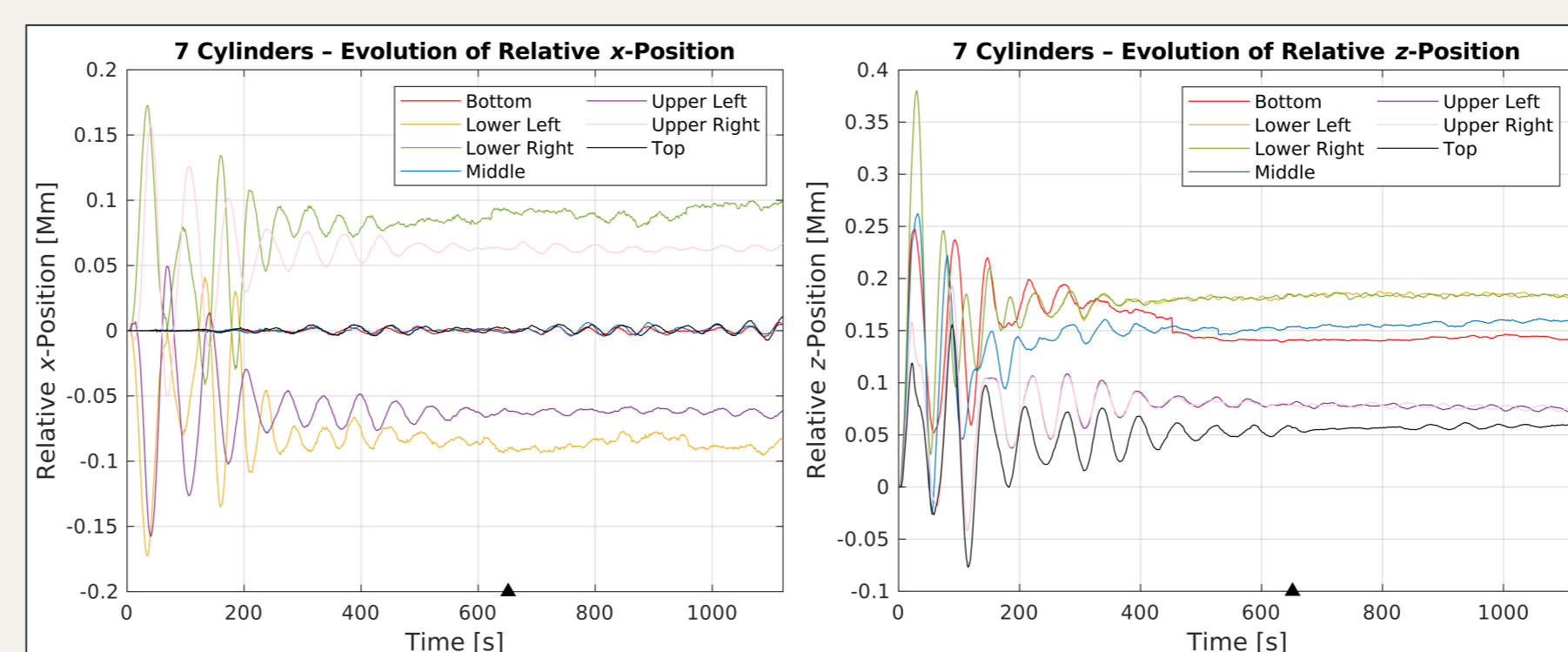


Figure 5. Left: evolution of approximate relative  $x$ -position; right: evolution of approximate relative  $z$ -position, i.e. displacement from initial positions, for Case #4, calculated by locating the density-weighted centre of the area identified as the transverse cross-section of the cylinder at  $y = 0$ . The mark indicates the time to which the relating mass density colormap (Fig. 3, right) corresponds.

- All cases: initial deformations of the cylinders.
- Cases #1, #2 and #3: symmetry of the wake is sufficiently broken → VS → KVS
- Cases #1, #2 (only configuration  $2r$ , i.e. cylinders in contact) and #3, i.e. when no horizontal gaps between the cylinders are set: VS triggers horizontal kink-mode oscillations (Cases #1 and #3) and oscillations with both  $x$ - and  $z$ -components (Case #2, configuration  $2r$ )
  - Estimated period values vary around 57 s (obtained by the software created by Torrence & Compo, 1998)
  - Case #2, configuration  $2r$ : anti-phase and in-phase oscillations of the cylinders in the  $z$ - and  $x$ -directions, respectively
  - Case #3: phase shifts and height-dependent oscillation periods
- Case #4: symmetry of the wake does not break significantly → no VS

## Conclusions

We present results of 3D ideal magnetohydrodynamic numerical simulations of plasma flow interacting with single and multiple cylindrical structures representing prominence threads in the solar atmosphere.

The results suggest horizontal separation between the magnetic structures can suppress coherent vortex-driven oscillations despite the presence of local vortex shedding. This highlights the importance of fine-scale structuring in determining the dynamical response of prominences.

Our results support the idea that vortex shedding may contribute to the excitation of transverse oscillations in solar prominences, particularly in multi-thread systems with favourable geometrical configurations. This mechanism may therefore play a role in the interpretation of observed prominence oscillations and in the broader context of coronal seismology.

## References

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- Nakariakov, V. M., Aschwanden, M. J., & Van Doorselaere, T. 2009, *A&A*, 502, 661–664
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