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► **To cite this version:**

Van-Sang Ngo, Geneviève Raugel. Approximative Controllability of Second Grade Fluids. 2019.
hal-01118496v2

HAL Id: hal-01118496

<https://hal.science/hal-01118496v2>

Preprint submitted on 21 Oct 2019

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APPROXIMATE CONTROLLABILITY OF SECOND GRADE FLUIDS

VAN-SANG NGO AND GENEVIÈVE RAUGEL

ABSTRACT. This paper deals with the controllability of the second grade fluids, a class of non-Newtonian of differential type, on a two-dimensional torus. Using the method of Agrachev-Sarychev [1], [2] and of Sirikyan [26], we prove that the system of second grade fluids is approximately controllable by a finite-dimensional control force.

1. INTRODUCTION

The goal of this paper is to study the approximate controllability of the system of fluids of second grade, using low-mode (finite-dimensional) control forces. More precisely, we consider the following system

$$(1.1) \quad \begin{cases} \partial_t (u - \alpha \Delta u) - \nu \Delta u + \operatorname{rot} (u - \alpha \Delta u) \times u + \nabla p = f + \eta \\ \operatorname{div} u = 0 \\ u(0) = u_0, \end{cases}$$

on the domain \mathbb{T}^2 , which is the two-dimensional torus $]0, 2\pi q_1[\times]0, 2\pi q_2[$, with $q_1 > 0$ and $q_2 > 0$. Here $u = (u_1(t, x), u_2(t, x))$ and $p = p(t, x)$ are unknown and represent the velocity vector field and the pressure function; $f = f(t, x)$ is the external force field; and the control force $\eta = \eta(t, x)$ is supposed to belong to a finite-dimensional space which will be made more precise later.

Fluids of second grade belong to a particular class of non-Newtonian Rivlin-Ericksen fluids of differential type [25], which usually arise in petroleum industry, in polymer technology or in liquid crystal suspension problems. For these fluids, the Cauchy stress tensor σ is not linearly proportional to the local strain rate but given by

$$(1.2) \quad \sigma = -pI + 2\nu A_1 + \alpha_1 A_2 + \alpha_2 A_1^2,$$

where ν stands for the kinematic viscosity, p is the pressure and A_1, A_2 represent the first two Rivlin-Ericksen tensors, which are

$$A_1(u) = \frac{1}{2} (\nabla u + \nabla u^T),$$

corresponding to the local strain tensor and

$$A_2(u) = \frac{DA_1}{Dt} + (\nabla u)^T A_1 + A_1 (\nabla u),$$

where

$$\frac{D}{Dt} = \partial_t + u \cdot \nabla$$

is the material derivative. In [7], Dunn and Fosdick used the compatibility of (1.2) with thermodynamics to prove that

$$\alpha_1 + \alpha_2 = 0; \quad \alpha_1 \geq 0.$$

1991 *Mathematics Subject Classification.* 35Q35, 93B05, 93C20.

Key words and phrases. Second grade fluid equations, approximate controllability, Agrachev-Sarychev method.

Setting $\alpha = \alpha_1$ and writing the equation

$$\frac{Du}{Dt} = \partial_t u + u \cdot \nabla u = \operatorname{div} \sigma + f,$$

one obtain the equations of second grade fluids of the following form

$$(1.3) \quad \begin{cases} \partial_t (u - \alpha \Delta u) - \nu \Delta u + \operatorname{rot} (u - \alpha \Delta u) \times u + \nabla p = f & \text{in } \mathbb{R}_+ \times \mathbb{T}^2 \\ \operatorname{div} u = 0 & \text{in } \mathbb{R}_+ \times \mathbb{T}^2 \\ u(0) = u_0 & \text{in } \mathbb{T}^2. \end{cases}$$

The local existence in time and uniqueness of a strong solution to (1.3) have been proven by Cioranescu and Ouazar in [6] in the case of two-dimensional or three-dimensional domains with non-slip boundary conditions. Moreover, the solution is global in time in the two-dimensional case. Second grade fluids in these domains were also studied by Moise, Rosa and Wang in [21], where the authors proved the existence of a compact global attractor in the two-dimensional case. The existence, the uniqueness of a strong solution and the dynamics of second grade fluids in the torus \mathbb{T}^2 was studied in [24] by Paicu, Raugel and Rekaló, and in [23] by the first two authors, using the Lagrangian approach. For further results concerning the system (1.3), we refer the readers to [3], [4], [5], [13], [14], [15], [16], [17], [18], [20], ...

In this paper, in order to study the approximate controllability of the second grade fluid system (1.1) by a low-mode control η , we use the method introduced by Agrachev and Sarychev in [1] and [2] for the Navier-Stokes and Euler systems in the two-dimensional torus \mathbb{T}^2 . This method was extended later for the three-dimensional Navier-Stokes system by Shirikyan in [26] and [27] and for the three-dimensional Euler system by Nersisyan in [22]. The main idea consists in proving that, if the (finite-dimensional) space of controls E contains sufficiently many Fourier modes then, for any $T > 0$, the system (1.1) is approximately controllable in time T by an E -valued control η .

Before stating the main results and the main ideas of this paper, we will introduce the needed notations and function spaces. Let $H^m(\mathbb{T}^2)^2$ be the classical Sobolev space of two-dimensional vector fields, whose components belong to $H^m(\mathbb{T}^2)$. For $m = 0$, we simply have $H^0(\mathbb{T}^2)^2 = L^2(\mathbb{T}^2)^2$. As in [24], for any $m \in \mathbb{N}$, we denote $V^m(\mathbb{T}^2)^2$ the closure of the space

$$\left\{ u \in C^\infty(\mathbb{T}^2)^2 \mid u \text{ is periodic, } \operatorname{div} u = 0, \int_{\mathbb{T}^2} u dx = 0 \right\}$$

in $H^m(\mathbb{T}^2)^2$. Then $V^m(\mathbb{T}^2)^2$ is a Banach space, endowed with the classical norm of $H^m(\mathbb{T}^2)^2$. For any $\theta > 0$, we define $V^\theta(\mathbb{T}^2)^2$ using the method of interpolation between $V^m(\mathbb{T}^2)^2$ spaces. Finally, we also use $H_{per}^m(\mathbb{T}^2)^2$ to denote the space of vector fields $u \in H^m(\mathbb{T}^2)^2$, which are periodic and whose mean value is zero.

In what follows, we recall the definition of a strong solution of the system (1.3).

Definition 1.1. *Let $T > 0$. For any $f \in L^\infty(0, T, H_{per}^1(\mathbb{T}^2)^2)$ and $u_0 \in V^3(\mathbb{T}^2)^2$, the vector field $u(t, x)$ is said to be a strong solution of the system (1.3), with data (f, u_0) , on the time interval $[0, T]$ if $u \in C(0, T, V^3(\mathbb{T}^2)^2)$, $\partial_t u \in L^\infty(0, T, V^2(\mathbb{T}^2)^2)$, $u(0) = u_0$, and for any $t \in]0, T]$, for any $\phi \in V^0(\mathbb{T}^2)^2$, the following equation holds*

$$(1.4) \quad \langle \partial_t (u(t) - \alpha \Delta u(t)) - \nu \Delta u(t) + \operatorname{rot} (u(t) - \alpha \Delta u(t)) \times u(t), \phi \rangle = \langle f(t), \phi \rangle.$$

In [24], the authors prove that

Theorem 1.2. *Let $\alpha > 0$ and $T > 0$.*

- (1) *For any $f \in L^\infty(0, T, H_{per}^1(\mathbb{T}^2)^2)$ and any $u_0 \in V^3(\mathbb{T}^2)^2$, there exists a unique strong solution*

$$u \in C(0, T, V^3(\mathbb{T}^2)^2) \cap W^{1,\infty}(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (1.3). Moreover, for any $t \in [0, T]$, the map

$$V^3(\mathbb{T}^2)^2 \ni u_0 \mapsto u(t) \in V^3(\mathbb{T}^2)^2$$

is continuous.

- (2) Let $m \geq 1$. Assume that $f \in L^\infty(0, T, H_{per}^{m+1}(\mathbb{T}^2)^2)$ and $u_0 \in V^{m+3}(\mathbb{T}^2)^2$. Then, the solution u of the system (1.3) belongs to $C(0, T, V^{m+3}(\mathbb{T}^2)^2)$.

For the system (1.1), we want to define the approximate controllability using low-mode controls. We will adapt the definition of approximate controllability given in [26] to the case of fluids of second grade.

Definition 1.3. Let $\theta > 0$, $T > 0$ and let E be a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. The second grade fluid system (1.1) is θ -approximately controllable (θ -AC) in time T by E -valued controls if, for any $\varepsilon > 0$, for any $u_0, u_T \in V^3(\mathbb{T}^2)^2$, there exist a control $\eta \in L^\infty(0, T, E)^2$ and a strong solution $u \in C(0, T, V^3(\mathbb{T}^2)^2)$ of the system (1.1) such that

$$\|u(T) - u_T\|_{V^\theta(\mathbb{T}^2)^2} \leq \varepsilon.$$

For any $m \in \mathbb{Z}^2 \setminus \{0\}$, let

$$c_m(x) = m^{q,\perp} \cos \langle m, x \rangle_q \quad \text{and} \quad s_m(x) = m^{q,\perp} \sin \langle m, x \rangle_q,$$

where $m^{q,\perp}$ will be defined in Section 5. Then, it is classical that c_m, s_m , with $m \in \mathbb{Z}^2 \setminus \{0\}$, are eigenvectors of the Stokes operator $-\mathbb{P}\Delta$, where \mathbb{P} is the Leray projection, and that the family $\{c_m, s_m \mid m \in \mathbb{Z}^2 \setminus \{0\}\}$ forms an orthonormal basis of $V^k(\mathbb{T}^2)^2$, $k \in \mathbb{N}$. For any $N \in \mathbb{N}^*$, we set

$$(1.5) \quad \mathcal{H}_q^N = \text{Span} \{c_m, s_m \mid m \in \mathbb{Z} \setminus \{0\}, |m| \leq N\}.$$

The main result of this paper is the following theorem.

Theorem 1.4. Let $T > 0$, $f \in L^\infty(0, T, H_{per}^2(\mathbb{T}^2)^2)$ and $u_0, u_T \in V^4(\mathbb{T}^2)$. Then the system (1.1) is 3-AC in time T by \mathcal{H}_q^3 -valued controls.

We note that, unlike the case of Navier-Stokes equations, the system of second grade fluids is an exemple of asymptotically smooth system, which only possesses a smoothing effect in infinite time. The systems (1.1) or (1.3) also differ from the α -type models, such as the so-called α -Navier-Stokes system (see [8], [9] and the references therein). Indeed, the α -Navier-Stokes system contains the very regularizing term $-\nu\Delta(u - \alpha\Delta u)$ instead of $-\nu\Delta u$, and thus is a semilinear problem, which is easier to solve. It is different in the case of second grade fluids where the dissipation is much weaker. This weak smoothing effect explains why in our result, we can not obtain an approximate control in the same norm as the initial data but only a control in the weaker norm. We also remark the similar phenomenon in [24], where the Navier-Stokes system is proved to be the limit of the second grade fluid system in $V^\theta(\mathbb{T}^2)^2$ for data in $V^3(\mathbb{T}^2)^2$ (respectively in $V^3(\mathbb{T}^2)^2$ for data in $V^4(\mathbb{T}^2)^2$).

Another problem when we want to apply the method of Shirikyan [26] lies in the complexity of the nonlinear term and the appearance of the term $\partial_t(-\alpha\Delta u)$. To avoid this difficulty, let

$$\mathcal{U} = u - \alpha\Delta u \quad \text{and} \quad \mathcal{U}_0 = u_0 - \alpha\Delta u_0$$

and let us rewrite the system (1.1) in the following form

$$(1.6) \quad \begin{cases} \partial_t \mathcal{U} + \mathcal{L}\mathcal{U} + \mathcal{B}(\mathcal{U}, \mathcal{U}) = \mathbb{P}f + \eta \\ \text{div} \mathcal{U} = 0 \\ \mathcal{U}(0) = \mathcal{U}_0, \end{cases}$$

where

$$(1.7) \quad \begin{cases} \mathcal{L}\mathcal{U} = -\nu\mathbb{P}\Delta(I - \alpha\Delta)^{-1}\mathcal{U} \\ \mathcal{B}(\mathcal{U}_1, \mathcal{U}_2) = \mathbb{P}(\text{rot} \mathcal{U}_1 \times ((I - \alpha\Delta)^{-1}\mathcal{U}_2)). \end{cases}$$

Along with the system (1.6), we consider the following controlled system

$$(1.8) \quad \begin{cases} \partial_t \mathcal{U} + \mathcal{L}(\mathcal{U} + \zeta) + \mathcal{B}(\mathcal{U} + \zeta, \mathcal{U} + \zeta) = \mathbb{P}f + \eta \\ \operatorname{div} \mathcal{U} = 0 \\ \mathcal{U}(0) = \mathcal{U}_0. \end{cases}$$

As in [1] or [26], we give the following definition

Definition 1.5. For any finite-dimensional subspace E of $V^3(\mathbb{T}^2)^2$, we define $\mathcal{F}(E)$ as the largest vector subspace of $V^3(\mathbb{T}^2)^2$ such that, $\mathcal{F}(E) \supset E$, and if $\bar{\eta} \in \mathcal{F}(E) \setminus E$ then, there exist

$$k \in \mathbb{N}^*, \alpha_1, \dots, \alpha_k > 0, \eta, \rho^1, \dots, \rho^k \in E$$

satisfying

$$\bar{\eta} = \eta - \sum_{j=1}^k \alpha_j \mathcal{B}(\rho^j, \rho^j).$$

The main idea to prove Theorem 1.4 is to extend the space of control E to the larger space $\mathcal{F}(E)$. To this end, we will prove the following theorems.

Theorem 1.6. Let $T > 0$ and E a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. Then, the system (1.6) is (θ -) approximately controllable in time T by an E -valued control η if and only if so is the system (1.8) with E -valued controls η and ζ .

Theorem 1.7. Let $T > 0$ and E a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. Then, the system (1.8) is approximately controllable in time T by E -valued controls η and ζ if and only if so is the system (1.8) with $\mathcal{F}(E)$ -valued controls η .

As a consequence of these theorems, the approximate controllability by E -valued controls is equivalent to the approximate controllability by $\mathcal{F}(E)$ -valued controls. We can define a sequence of subspace

$$E = E_0 \subset E_1 \subset \dots \subset E_n \subset \dots$$

such that, for any $n \in \mathbb{N}$ we have $E_{n+1} = \mathcal{F}(E_n)$. The only problem is that $\mathcal{F}(E)$ may be not larger than E . However, if we can choose E in such a way that the space

$$E_\infty = \bigcup_{n=0}^{\infty} E_n$$

is dense in $V^1(\mathbb{T}^2)^2$, then the approximate controllability E -valued controls will follow. Indeed, for $T > 0$, $\varepsilon > 0$, $u_0, u_T \in V^4(\mathbb{T}^2)^2$, we set

$$\mathcal{U}_0 = u_0 - \alpha \Delta u_0 \quad \text{and} \quad \mathcal{U}_T = u_T - \alpha \Delta u_T.$$

Then, we can always exactly control the system (1.6) by the control

$$\eta = \partial_t \bar{\mathcal{U}} + \mathcal{L} \bar{\mathcal{U}} + \mathcal{B}(\bar{\mathcal{U}}) - \mathbb{P}f \in L^\infty(0, T, V^1(\mathbb{T}^2)^2),$$

where

$$\bar{\mathcal{U}}(t) = \frac{1}{T} (I - \alpha \Delta) ((T - t)u_0 + tu_T).$$

Thus, if E_∞ is dense in $V^1(\mathbb{T}^2)^2$, then there exists $n \in \mathbb{N}$ large enough such that the system (1.6) is approximately controllable by E_n -valued controls. Using Theorems 1.6 and 1.7, we can prove by induction that (1.6) is approximately controllable by E -valued controls. In order to prove Theorem 1.4, we only need to prove the following result

Theorem 1.8. If $E = \mathcal{H}_q^3$ then $E_\infty \supset \mathcal{H}_q^N$, for any $N \in \mathbb{N}$, $N \geq 3$.

The paper will be organized as follows. In Section 2, we study a perturbation of the system (1.6), which is necessary to prove our main theorem. Theorem 1.6 will be proved in Section 3. Section 4 is devoted to the demonstration of Theorem 1.7. In Section 5, we put in evidence the saturation property given in Theorem 1.8. Finally, in the last section, we will prove the main theorem 1.4.

2. PRELIMINARY RESULTS ON THE SYSTEM OF FLUIDS OF SECOND GRADE

In this section, we consider the following perturbed system of fluids of second grade

$$(2.1) \quad \begin{cases} \partial_t \mathcal{W} + \mathcal{L}\mathcal{W} + \mathcal{B}(\mathcal{W}) + \mathcal{B}(\mathcal{W}, \mathcal{V}) + \mathcal{B}(\mathcal{V}, \mathcal{W}) = \mathbb{P}f & \text{in } \mathbb{T}^2 \times [0, T] \\ \operatorname{div} \mathcal{W} = 0 & \text{in } \mathbb{T}^2 \times [0, T] \\ \mathcal{W}(0) = \mathcal{W}_0 & \text{in } \mathbb{T}^2, \end{cases}$$

where $\mathcal{V} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2)$, $f \in L^\infty(0, T, H_{per}^1(\mathbb{T}^2)^2)$. We want to prove that

Theorem 2.1. *Let $T > 0$ fixed.*

1. *For any $\mathcal{V} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2)$, $f \in L^\infty(0, T, H_{per}^1(\mathbb{T}^2)^2)$ and $\mathcal{W}_0 \in V^1(\mathbb{T}^2)^2$, the system (2.1) has a unique solution*

$$\mathcal{W} \in L^\infty(0, T, V^1(\mathbb{T}^2)^2) \cap C(0, T, V^1(\mathbb{T}^2)^2).$$

Moreover, if $\mathcal{V} \in L^\infty(0, T, V^3(\mathbb{T}^2)^2)$, $f \in L^\infty(0, T, H_{per}^2(\mathbb{T}^2)^2)$ and $\mathcal{W}_0 \in V^2(\mathbb{T}^2)^2$ then

$$\mathcal{W} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2).$$

2. *Let \mathcal{W} and $\widehat{\mathcal{W}}$ be two solutions of the system (2.1), corresponding to data $(\mathcal{V}, f, \mathcal{W}_0)$ and $(\widehat{\mathcal{V}}, \widehat{f}, \widehat{\mathcal{W}}_0)$ respectively. Then, if*

$$\widehat{\mathcal{W}} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2),$$

then, there exists a constant $C > 0$ such that, for any $t \in [0, T]$, we have

$$(2.2) \quad \left\| \mathcal{W}(t) - \widehat{\mathcal{W}}(t) \right\|_{V^1(\mathbb{T}^2)^2} \leq C \left(\left\| \mathcal{V} - \widehat{\mathcal{V}} \right\|_{L^2(0, T, V^2)^2} + \left\| \mathbb{P}f - \mathbb{P}\widehat{f} \right\|_{L^2(0, T, V^1)^2} + \left\| \mathcal{W}_0 - \widehat{\mathcal{W}}_0 \right\|_{V^1(\mathbb{T}^2)^2} \right).$$

We remark that if we set

$$\begin{cases} v = (I - \alpha\Delta)^{-1}\mathcal{V} \\ w_0 = (I - \alpha\Delta)^{-1}\mathcal{W}_0 \\ w = (I - \alpha\Delta)^{-1}\mathcal{W} \end{cases}$$

then, w is solution of the following system

$$(2.3) \quad \begin{cases} \partial_t(w - \alpha\Delta w) - \nu\Delta w + \mathbb{P}B(w) + \mathbb{P}B(w, v) + \mathbb{P}B(v, w) = \mathbb{P}f \\ \operatorname{div} w = 0 \\ w(0) = w_0, \end{cases}$$

where

$$B(u_1, u_2) = \operatorname{rot}(u_1 - \alpha\Delta u_1) \times u_2 \quad \text{and} \quad B(u) = B(u, u).$$

Theorem 2.1 is in fact equivalent to the following theorem for the system (2.3)

Theorem 2.2. *Let $T > 0$ fixed.*

1. *For any $v \in L^\infty(0, T, V^4(\mathbb{T}^2)^2)$, $f \in L^\infty(0, T, H_{per}^1(\mathbb{T}^2)^2)$ and $w_0 \in V^3(\mathbb{T}^2)^2$, the system (2.3) has a unique solution*

$$w \in L^\infty(0, T, V^3(\mathbb{T}^2)^2) \cap C(0, T, V^3(\mathbb{T}^2)^2).$$

Moreover, if $v \in L^\infty(0, T, V^3(\mathbb{T}^2)^2)$, $f \in L^\infty(0, T, H_{per}^2(\mathbb{T}^2)^2)$ and $w_0 \in V^2(\mathbb{T}^2)^2$ then

$$w \in L^\infty(0, T, V^4(\mathbb{T}^2)^2) \cap C(0, T, V^4(\mathbb{T}^2)^2).$$

2. *Let w and \widehat{w} be two solutions of the system (2.3), corresponding to data (v, f, w_0) and $(\widehat{v}, \widehat{f}, \widehat{w}_0)$ respectively. Then, if*

$$\widehat{w} \in L^\infty(0, T, V^4(\mathbb{T}^2)^2) \cap C(0, T, V^4(\mathbb{T}^2)^2),$$

then, there exists a constant $C > 0$ such that, for any $t \in [0, T]$, we have

$$(2.4) \quad \|w(t) - \widehat{w}(t)\|_{V^3(\mathbb{T}^2)^2} \leq C \left(\|v - \widehat{v}\|_{L^2(0, T, V^4)^2} + \|\mathbb{P}f - \mathbb{P}\widehat{f}\|_{L^2(0, T, V^1)^2} + \|w_0 - \widehat{w}_0\|_{V^3(\mathbb{T}^2)^2} \right).$$

We remark that the proof of the existence of solutions of the systems (2.1) and (2.3) follows the lines of the proof of [[24], Theorems 2.1 and 2.4]. In what follows, we give the needed *a priori* estimates to prove (2.2) and (2.4). We will set

$$(2.5) \quad \begin{aligned} \mathcal{W} &= \text{rot}(w - \alpha \Delta w), & \widehat{\mathcal{W}} &= \text{rot}(\widehat{w} - \alpha \Delta \widehat{w}) \\ \mathcal{V} &= \text{rot}(v - \alpha \Delta v), & \widehat{\mathcal{V}} &= \text{rot}(\widehat{v} - \alpha \Delta \widehat{v}) \\ \mathcal{O} &= \mathcal{W} - \widehat{\mathcal{W}}. \end{aligned}$$

2.1. Propagation of the V^3 -norm. In this paragraph, we give a priori estimates of a solution of the system (2.3) in $V^3(\mathbb{T}^2)$ -norm. Applying the rot operator to the first equation of (2.3), we obtain

$$(2.6) \quad \partial_t \mathcal{W} + \frac{\nu}{\alpha} \mathcal{W} + \mathbb{P}(w \cdot \nabla \mathcal{W}) + \mathbb{P}(v \cdot \nabla \mathcal{W}) + \mathbb{P}(w \cdot \nabla \mathcal{V}) = \text{rot } \mathbb{P}f + \frac{\nu}{\alpha} \text{rot } w.$$

Since v and w are divergence-free vector fields on \mathbb{T}^2 , integrations by parts show that

$$\langle w \cdot \nabla \mathcal{W}, \mathcal{W} \rangle_{L^2(\mathbb{T}^2)^2} = \langle v \cdot \nabla \mathcal{W}, \mathcal{W} \rangle_{L^2(\mathbb{T}^2)^2} = 0.$$

As a consequence, taking the $L^2(\mathbb{T}^2)^2$ inner product of (2.6) with \mathcal{W} , we get

$$(2.7) \quad \begin{aligned} \frac{1}{2} \frac{d}{dt} \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2}^2 + \frac{\nu}{\alpha} \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2}^2 &\leq \left| \langle w \cdot \nabla \mathcal{V}, \mathcal{W} \rangle_{L^2(\mathbb{T}^2)^2} \right| + \left| \langle \text{rot } f, \mathcal{W} \rangle_{L^2(\mathbb{T}^2)^2} \right| + \frac{\nu}{\alpha} \left| \langle \text{rot } w, \mathcal{W} \rangle_{L^2(\mathbb{T}^2)^2} \right| \\ &\leq \|\text{rot } f\|_{L^2(\mathbb{T}^2)^2} \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2} + \left(\|\nabla \mathcal{V}\|_{L^2(\mathbb{T}^2)^2} + \frac{\nu}{\alpha} \right) \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2}^2, \end{aligned}$$

which implies that

$$(2.8) \quad \frac{d}{dt} \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2}^2 \leq \|f\|_{V^1(\mathbb{T}^2)^2}^2 + 2 \left(1 + \|v\|_{V^4(\mathbb{T}^2)^2} \right) \|\mathcal{W}\|_{L^2(\mathbb{T}^2)^2}^2.$$

Finally, the Gronwall lemma gives, for any $0 \leq t \leq T$,

$$(2.9) \quad \|\mathcal{W}(t)\|_{L^2(\mathbb{T}^2)^2}^2 \leq \left(\|\mathcal{W}(0)\|_{L^2(\mathbb{T}^2)^2}^2 + \|f\|_{L^\infty(0, T, V^1(\mathbb{T}^2)^2)}^2 \right) \exp \left\{ 2t \left(1 + \|v\|_{L^\infty(0, T, V^4(\mathbb{T}^2)^2)} \right) \right\}.$$

2.2. A priori estimates of the difference of two solutions in V^3 -norm. Using the same notations as in [6], [24] or [23], we identify a 2D vector (u_1, u_2) with the 3D vector $(u_1, u_2, 0)$ and a scalar λ with the 3D vector $(0, 0, \lambda)$. We also recall the identity

$$\operatorname{rot}(\operatorname{rot}(a) \times b) = b \cdot \nabla \operatorname{rot}(a),$$

where a and b are 2D vector fields and $\operatorname{div} v = 0$. We deduce from (2.3) that \mathcal{W} and $\widehat{\mathcal{W}}$ are solutions of the following equation, with data (v, f, w_0) and $(\widehat{v}, \widehat{f}, \widehat{w}_0)$ respectively.

$$(2.10) \quad \partial_t \mathcal{W} + \frac{\nu}{\alpha} \mathcal{W} + \mathbb{P}(w \cdot \nabla \mathcal{W}) + \mathbb{P}(v \cdot \nabla \mathcal{W}) + \mathbb{P}(w \cdot \nabla \mathcal{V}) = \operatorname{rot} \mathbb{P}f + \frac{\nu}{\alpha} \operatorname{rot} w.$$

The calculation of the difference between the equations corresponding to \mathcal{W} and $\widehat{\mathcal{W}}$ shows that $\mathcal{O} = \mathcal{W} - \widehat{\mathcal{W}}$ satisfies the following equation

$$(2.11) \quad \begin{aligned} \partial_t \mathcal{O} + \frac{\nu}{\alpha} \mathcal{O} + \mathbb{P}(w \cdot \nabla \mathcal{O}) + \mathbb{P}((w - \widehat{w}) \cdot \nabla \widehat{\mathcal{W}}) + \mathbb{P}(v \cdot \nabla \mathcal{O}) + \mathbb{P}((v - \widehat{v}) \cdot \nabla \widehat{\mathcal{W}}) \\ + \mathbb{P}(w \cdot \nabla (\mathcal{V} - \widehat{\mathcal{V}})) + \mathbb{P}((w - \widehat{w}) \cdot \nabla \widehat{\mathcal{V}}) = \operatorname{rot}(\mathbb{P}f - \mathbb{P}\widehat{f}) + \frac{\nu}{\alpha} \operatorname{rot}(w - \widehat{w}). \end{aligned}$$

Next, we will take the L^2 inner product of (2.11) with \mathcal{O} .

Using the divergence-free property of v and w , we have

$$(2.12) \quad \langle v \cdot \nabla \mathcal{O}, \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} = \langle w \cdot \nabla \mathcal{O}, \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} = 0.$$

Now, using Hölder's and Cauchy-Schwarz's inequalities, we get

$$(2.13) \quad \begin{aligned} \left| \langle (w - \widehat{w}) \cdot \nabla \widehat{\mathcal{W}}, \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} \right| &\leq \left\| \nabla \widehat{\mathcal{W}} \right\|_{L^2(\mathbb{T}^2)^2} \|w - \widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \left\| \nabla \widehat{\mathcal{W}} \right\|_{L^2(\mathbb{T}^2)^2} \|w - \widehat{w}\|_{V^3(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|\widehat{w}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2. \end{aligned}$$

The same calculations give

$$(2.14) \quad \begin{aligned} \left| \langle (v - \widehat{v}) \cdot \nabla \widehat{\mathcal{W}}, \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} \right| &\leq C \left\| \nabla \widehat{\mathcal{W}} \right\|_{L^2(\mathbb{T}^2)^2} \|v - \widehat{v}\|_{L^\infty(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|\widehat{w}\|_{V^4(\mathbb{T}^2)^2} \left(\|v - \widehat{v}\|_{V^3(\mathbb{T}^2)^2}^2 + \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2 \right), \end{aligned}$$

$$(2.15) \quad \begin{aligned} \left| \langle w \cdot \nabla (\mathcal{V} - \widehat{\mathcal{V}}), \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} \right| \\ &\leq \|w\|_{L^\infty(\mathbb{T}^2)^2} \left\| \nabla (\mathcal{V} - \widehat{\mathcal{V}}) \right\|_{L^2(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|w\|_{L^\infty(\mathbb{T}^2)^2} \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \left(\|w - \widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} + \|\widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} \right) \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \left(\|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} + \|\widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} \right) \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|\widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2}^2 + C \left(\|\widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} + \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2} \right) \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2, \end{aligned}$$

$$(2.16) \quad \begin{aligned} \left| \langle (w - \widehat{w}) \cdot \nabla \widehat{\mathcal{V}}, \mathcal{O} \rangle_{L^2(\mathbb{T}^2)^2} \right| &\leq \|w - \widehat{w}\|_{L^\infty(\mathbb{T}^2)^2} \left\| \nabla \widehat{\mathcal{V}} \right\|_{L^2(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|w - \widehat{w}\|_{V^3(\mathbb{T}^2)^2} \|\widehat{v}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \\ &\leq C \|\widehat{v}\|_{V^4(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2. \end{aligned}$$

For the forcing term, we have

$$(2.17) \quad \left| \left\langle \operatorname{rot}(\mathbb{P}f - \mathbb{P}\widehat{f}), \mathcal{O} \right\rangle_{L^2(\mathbb{T}^2)^2} \right| \leq C \left(\left\| \mathbb{P}f - \mathbb{P}\widehat{f} \right\|_{V^1(\mathbb{T}^2)^2}^2 + \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2 \right),$$

and finally,

$$(2.18) \quad \left| \left\langle \operatorname{rot}(w - \widehat{w}), \mathcal{O} \right\rangle_{L^2(\mathbb{T}^2)^2} \right| \leq \|\operatorname{rot}(w - \widehat{w})\|_{L^2(\mathbb{T}^2)^2} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2} \leq C \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2.$$

Now, using Estimates (2.12) to (2.18), we obtain

$$\begin{aligned} & \frac{1}{2} \frac{d}{dt} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2 + \frac{\nu}{\alpha} \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2 \\ & \leq C \|\widehat{w}\|_{V^4(\mathbb{T}^2)^2} \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2}^2 + C \left\| \mathbb{P}f - \mathbb{P}\widehat{f} \right\|_{V^1(\mathbb{T}^2)^2}^2 \\ & \quad + C \left(1 + \|\widehat{w}\|_{V^4(\mathbb{T}^2)^2} + \|\widehat{v}\|_{V^4(\mathbb{T}^2)^2} + \|v - \widehat{v}\|_{V^4(\mathbb{T}^2)^2} \right) \|\mathcal{O}\|_{L^2(\mathbb{T}^2)^2}^2. \end{aligned}$$

For any $0 \leq t \leq T$, the Gronwall lemma implies that

$$(2.19) \quad \|\mathcal{O}(t)\|_{L^2(\mathbb{T}^2)^2}^2 \leq C e^{C_2 t} \left(\|w(0) - \widehat{w}(0)\|_{V^3(\mathbb{T}^2)^2}^2 + T \left\| \mathbb{P}f - \mathbb{P}\widehat{f} \right\|_{L_t^\infty V^1(\mathbb{T}^2)^2}^2 + C_1 T \|v - \widehat{v}\|_{L_t^\infty V^4(\mathbb{T}^2)^2}^2 \right),$$

where C is a generic positive constant and

$$\begin{aligned} C_1 &= \|\widehat{w}\|_{L^\infty(0, T, V^4(\mathbb{T}^2)^2)}, \\ C_2 &= 1 + \|\widehat{w}\|_{L^\infty(0, T, V^4(\mathbb{T}^2)^2)} + \|\widehat{v}\|_{L^\infty(0, T, V^4(\mathbb{T}^2)^2)} + \|v - \widehat{v}\|_{L^\infty(0, T, V^4(\mathbb{T}^2)^2)}. \end{aligned}$$

The inequality (2.4) of Theorem 2.2 is then proved.

3. STUDY OF THE EXTENDED CONTROLLED SYSTEM

In this section, we want to show that the approximate controllability of the system (1.6) is equivalent to the approximate controllability of the system (1.8) by low-mode controls. For any finite-dimensional subspace E of $V^3(\mathbb{T}^2)^2$, we remark that the approximate controllability of the system (1.6) by E -valued controls implies immediately the approximate controllability of the system (1.8) in the same space of controls. Indeed, we only need to choose $\zeta = 0$ in the system (1.8). Then, in order to prove Theorem 1.6, we only need to prove the following result

Theorem 3.1. *Let $T > 0$ and E be a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. Let η, ζ in $L^\infty(0, T, E)^2$ and*

$$\mathcal{U} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

be a solution of (1.8). Then, for any $k \in \mathbb{N}^$, there are a control $\eta_k \in L^\infty(0, T, E)^2$ and a solution*

$$\mathcal{U}_k \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (1.6), with $\eta = \eta_k$, such that $\mathcal{U}_k(0) = \mathcal{U}_0$, and

$$\|\mathcal{U}_k(T) - \mathcal{U}(T)\|_{V^3(\mathbb{T}^2)^2} \leq \frac{1}{k}.$$

Proof. First of all, we can rewrite the system (1.8) as

$$(3.1) \quad \begin{cases} \partial_t \mathcal{U} + \mathcal{L}\mathcal{U} + \mathcal{B}(\mathcal{U}, \mathcal{U}) + \mathcal{B}(\mathcal{U}, \zeta) + \mathcal{B}(\zeta, \mathcal{U}) = \mathbb{P}f + \eta - \mathcal{L}\zeta - \mathcal{B}(\zeta, \zeta) \\ \operatorname{div} \mathcal{U} = 0 \\ \mathcal{U}(0) = \mathcal{U}_0, \end{cases}$$

where

$$\mathcal{L}\mathcal{U} = -\nu\mathbb{P}\Delta(I - \alpha\Delta)^{-1}\mathcal{U} \quad \text{and} \quad \mathcal{B}(\mathcal{U}_1, \mathcal{U}_2) = \mathbb{P}(\text{rot}\mathcal{U}_1 \times ((I - \alpha\Delta)^{-1}\mathcal{U}_2)).$$

Thus, applying Theorem 2.1 to this system, for any $\eta, \zeta \in L^\infty(0, T, E)^2$, we obtain the existence of a unique solution of the system (3.1) (or (1.8))

$$\bar{\mathcal{U}} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2).$$

Next, we remark that we can also rewrite the system (1.8) as

$$(3.2) \quad \begin{cases} \partial_t(\mathcal{U} + \zeta) + \mathcal{L}(\mathcal{U} + \zeta) + \mathcal{B}(\mathcal{U} + \zeta) = \mathbb{P}f + \tilde{\eta} \\ \text{div}\mathcal{U} = 0 \\ \mathcal{U}(0) = \mathcal{U}_0, \end{cases}$$

where

$$\tilde{\eta} = \eta + \partial_t\zeta,$$

which means that, if $\bar{\mathcal{U}}$ is a solution of the system (1.8) and if $\tilde{\eta}$ belongs to $L^\infty(0, T, E)^2$, then $\bar{\mathcal{U}} + \zeta$ is a solution of the system (1.6), with η replaced by $\tilde{\eta}$ and \mathcal{U}_0 by $\mathcal{U}_0 + \zeta(0)$. So, if we want to construct a solution of the controlled system (1.6) satisfying the conditions of Theorem 3.1, we only need to check whether the conditions at time $t = 0$ and $t = T$ are satisfied. To this end, we will consider a sequence of controls

$$\zeta_l \in C^1(0, T, E), \quad \forall l \in \mathbb{N}^*$$

such that

$$\zeta_l(0) = \zeta_l(T) = 0$$

and

$$\lim_{l \rightarrow +\infty} \|\zeta_l - \zeta\|_{L^2(0, T, V^2(\mathbb{T}^2)^2)} = 0.$$

Applying Theorem 2.1 to the system (3.1), for any $l \in \mathbb{N}^*$, there exists a unique solution

$$\bar{\mathcal{U}}_l \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (3.1) (or (1.8)), with ζ replaced by ζ_l . Moreover, for any $k \in \mathbb{N}^*$, there exists $l_0 \in \mathbb{N}^*$ such that, for any $l \geq l_0$, for any $t \in [0, T]$, we have

$$\|\bar{\mathcal{U}}_l(t) - \bar{\mathcal{U}}(t)\|_{V^1} \leq C \left(\|\zeta_l - \zeta\|_{L^2(V^2)} + \|\mathcal{L}\zeta_l - \mathcal{L}\zeta\|_{L^2(V^1)} + \|\mathcal{B}(\zeta_l, \zeta_l) - \mathcal{B}(\zeta, \zeta)\|_{L^2(V^1)} \right) \leq \frac{1}{k}.$$

Now, we set

$$\mathcal{U}_k = \bar{\mathcal{U}}_{l_0} + \zeta_{l_0} \quad \text{and} \quad \eta_k = \eta + \partial_t\zeta_{l_0}.$$

Then, \mathcal{U}_k is the solution of the system (1.6), with η replaced by $\eta_k \in L^\infty(0, T, E)^2$. Moreover, we have

$$\mathcal{U}_k(0) = \bar{\mathcal{U}}_{l_0}(0) + \zeta_{l_0}(0) = \bar{\mathcal{U}}_{l_0}(0) = \mathcal{U}_0,$$

and

$$\|\mathcal{U}_k(T) - \bar{\mathcal{U}}(T)\|_{V^1(\mathbb{T}^2)^2} = \|\bar{\mathcal{U}}_{l_0}(T) - \bar{\mathcal{U}}(T)\|_{V^1(\mathbb{T}^2)^2} \leq \frac{1}{k}.$$

Theorem 3.1 is proved. \blacksquare

4. CONVEXIFICATION OF THE CONTROLLED SYSTEM

This section is devoted to the proof of Theorem 1.7. From the definition 1.5 of $\mathcal{F}(E)$, we remark that $E \subset \mathcal{F}(E)$ and so, the approximate controllability of the system (1.1) (or (1.6)) by E -valued controls evidently implies the approximate controllability of the system (1.1) (or (1.6)) by $\mathcal{F}(E)$ -valued controls. In order to prove Theorem 1.7, we only need to prove that

Theorem 4.1. *Let $T > 0$, E be a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. Let $\bar{\eta}$ be a control in $L^\infty(0, T, \mathcal{F}(E))^2$ and*

$$\bar{\mathcal{U}} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

be a solution of (1.6), with η replaced by $\bar{\eta}$. Then, for any $k \in \mathbb{N}^$, there are controls $\eta_k, \zeta_k \in L^\infty(0, T, E)^2$ and a solution*

$$\mathcal{U}_k \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (1.8), with η replaced by η_k and ζ by ζ_k , such that $\mathcal{U}_k(0) = \mathcal{U}_0$, and

$$\lim_{k \rightarrow +\infty} \|\mathcal{U}_k(T) - \bar{\mathcal{U}}(T)\|_{V^1(\mathbb{T}^2)^2} = 0.$$

The proof of Theorem 4.1 will be divided into several steps.

Step 1. *Reduction of the proof of Theorem 4.1 to the case of $\mathcal{F}(E)$ -valued piecewise constant in time controls.*

We suppose that Theorem 4.1 is true for $\mathcal{F}(E)$ -valued piecewise constant controls. We want to prove that Theorem 4.1 is also true in the general case. Let $\bar{\eta} \in L^\infty(0, T, \mathcal{F}(E))$ and let

$$\bar{\mathcal{U}} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

be a solution of (1.6), with η replaced by $\bar{\eta}$. We consider an approximation of $\bar{\eta}$ by a sequence $\{\eta^m\}$ of $\mathcal{F}(E)$ -valued piecewise constant in time controls such that

$$\lim_{m \rightarrow +\infty} \|\eta^m - \bar{\eta}\|_{L^2(0, T, V^2(\mathbb{T}^2)^2)} = 0.$$

Applying Theorem 2.1 (while taking $\mathcal{V} = 0$ and replacing f by $f + \eta^m$ and $f + \bar{\eta}$), we deduce the existence of a solution

$$\mathcal{U}^m \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (1.6), with η replaced by η^m , such that

$$\sup_{t \in [0, T]} \|\mathcal{U}^m(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} \leq C \left(\|\bar{\mathcal{U}}\|_{L^2(0, T, V^2(\mathbb{T}^2)^2)} \right) \|\eta^m - \bar{\eta}\|_{L^2(0, T, V^2(\mathbb{T}^2)^2)} \leq \frac{\varepsilon}{2},$$

for any m larger than a certain $m_0 \in \mathbb{N}^*$.

If Theorem 4.1 is true for $\mathcal{F}(E)$ -valued piecewise constant controls, we deduce the existence of η and ζ in $L^\infty(0, T, E)^2$, and a solution

$$\mathcal{U} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

of the system (1.8) such that

$$\mathcal{U}(0) = \mathcal{U}^{m_0}(0) = \bar{\mathcal{U}}(0),$$

and

$$\sup_{t \in [0, T]} \|\mathcal{U}(t) - \mathcal{U}^{m_0}(t)\|_{V^1(\mathbb{T}^2)^2} \leq \frac{\varepsilon}{2}.$$

Therefore,

$$\sup_{t \in [0, T]} \|\mathcal{U}(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} \leq \sup_{t \in [0, T]} \|\mathcal{U}(t) - \mathcal{U}^{m_0}(t)\|_{V^1(\mathbb{T}^2)^2} + \sup_{t \in [0, T]} \|\mathcal{U}^{m_0}(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} \leq \varepsilon.$$

Remark 4.2. *Using an argument by iteration, we can reduce the study to the case where the control $\bar{\eta}$ is constant in time. So from now on, we will consider $\bar{\eta} \in \mathcal{F}(E)$, which is constant in the time variable.*

Step 2. *Construction of solutions of the extended controlled system (1.8).*

The construction of controls η_k, ζ_k and a solution \mathcal{U}_k of the controlled system (1.8), with (η, ζ) replaced by (η_k, ζ_k) , follows the lines of the construction in [26] (see also [1] and [2]). We recall that

$$\bar{\mathcal{U}} \in L^\infty(0, T, V^2(\mathbb{T}^2)^2) \cap C(0, T, V^2(\mathbb{T}^2)^2)$$

is the solution of the controlled system (1.6), with η replaced by $\bar{\eta} \in \mathcal{F}(E)$. Let $\varepsilon > 0$ and $\delta > 0$ which will be made more precise later and choose $N > 0$ large enough such that

$$\|\mathbb{P}f - P_N \mathbb{P}f\|_{L^2(0, T, V^1(\mathbb{T}^2)^2)} + \|\mathcal{U}_0 - P_N \mathcal{U}_0\|_{V^1(\mathbb{T}^2)^2} \leq \delta,$$

where P_N is the projection onto the space of the first N eigenvectors of the Stokes operator $-\mathbb{P}\Delta$ and where \mathbb{P} is the Leray projection onto the subspace of divergence-free vector fields of $L^2(\mathbb{T}^2)^2$. Let

$$\mathcal{V}_0 = P_N \mathcal{U}_0$$

and \mathcal{V}_N be the solution of the system

$$(4.1) \quad \begin{cases} \partial_t \mathcal{V}_N + \mathcal{L}\mathcal{V}_N + \mathcal{B}(\mathcal{V}_N) = \mathbb{P}P_N f + \bar{\eta} \\ \operatorname{div} \mathcal{V}_N = 0 \\ \mathcal{V}_N(0) = \mathcal{V}_0 = P_N \mathcal{U}_0. \end{cases}$$

Using the definition in (1.7), we remark that $(I - \alpha\Delta)^{-1}\mathcal{V}_N$ is the solution of the system (1.1), with $u_0 = (I - \alpha\Delta)^{-1}P_N \mathcal{U}_0$ and η replaced by $\bar{\eta}$. Then, applying [[24], Theorems 2.1 and 2.4], we obtain the existence of a unique solution

$$\mathcal{V}_N \in L^\infty(0, T, V^3(\mathbb{T}^2)^2) \cap C(0, T, V^3(\mathbb{T}^2)^2)$$

of the system (4.1). The following lemma (see [26]) allows us to have a ‘‘good decomposition’’ of $\mathcal{F}(E)$ -valued controls in terms of E -valued controls.

Lemma 4.3. *Let E be a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$. Then, for any $\bar{\eta} \in \mathcal{F}(E) \setminus E$, there exist $m \in \mathbb{N}^*$; $\eta, \rho^1, \dots, \rho^m \in E$ and $\lambda_1, \dots, \lambda_m \in \mathbb{R}_+$, with $\sum_{j=1}^m \lambda_j = 1$, such that, for any $\mathcal{U} \in V^2(\mathbb{T}^2)^2$, we have*

$$\mathcal{B}(\mathcal{U}) - \bar{\eta} = \sum_{j=1}^m \lambda_j (\mathcal{B}(\mathcal{U} + \rho^j) + \mathcal{L}\rho^j) - \eta.$$

Proof. Since $\bar{\eta} \in \mathcal{F}(E) \setminus E$, Definition 1.5 implies that there exist

$$k \in \mathbb{N}^*; \alpha_1, \dots, \alpha_k > 0; \text{ and } \tilde{\eta}, \tilde{\rho}^1, \dots, \tilde{\rho}^k \in E$$

such that

$$\bar{\eta} = \tilde{\eta} - \sum_{j=1}^k \alpha_j \mathcal{B}(\tilde{\rho}^j).$$

Let $m = 2k$, $\alpha = \alpha_1 + \dots + \alpha_k$ and

$$\begin{cases} \lambda_j = \frac{\alpha_j}{2\alpha}, \rho^j = \sqrt{\alpha} \tilde{\rho}^j, \quad \forall j \in \{1, \dots, k\} \\ \lambda_j = \frac{\alpha_{j-k}}{2\alpha}, \rho^j = -\sqrt{\alpha} \tilde{\rho}^{j-k}, \quad \forall j \in \{k+1, \dots, m\}. \end{cases}$$

We remark that, for any $j \in \{1, \dots, k\}$, we have

$$\lambda_j = \lambda_{j+k} \quad \text{and} \quad \rho^j = -\rho^{j+k}.$$

Then, for any $\mathcal{U} \in V^2(\mathbb{T}^2)^2$, direct calculations give,

$$\mathcal{B}(\mathcal{U}, \mathcal{U}) - \bar{\eta} = \sum_{j=1}^m \lambda_j (\mathcal{B}(\mathcal{U} + \rho^j) + \mathcal{L}\rho^j) - \eta. \quad \blacksquare$$

Lemma 4.3 allows us to rewrite the system (4.1) as follows

$$(4.2) \quad \begin{cases} \partial_t \mathcal{V}_N + \mathcal{L}\mathcal{V}_N + \sum_{j=1}^m \lambda_j (\mathcal{B}(\mathcal{V}_N + \rho^j) + \mathcal{L}\rho^j) = \mathbb{P}P_N f + \eta \\ \operatorname{div} \mathcal{V}_N = 0 \\ \mathcal{V}_N(0) = \mathcal{V}_0 = P_N \mathcal{U}_0. \end{cases}$$

Now, we use the same construction as explained in [26] to build the needed additional control ζ in the system (1.8). To this end, we introduce the following 1-periodic function $\varphi : \mathbb{R}_+ \rightarrow E$

$$(4.3) \quad \begin{cases} \varphi(s) = \varphi(s+1) & \text{for any } s \in \mathbb{R}_+ \\ \varphi(s) = \rho^1 & \text{si } 0 \leq s < \lambda_1 \\ \varphi(s) = \rho^j & \text{si } \lambda_1 + \dots + \lambda_{j-1} \leq s < \lambda_1 + \dots + \lambda_j, \quad \text{for any } 2 \leq j \leq m \end{cases}$$

For any $k \geq 1$, let

$$(4.4) \quad \psi_k(t) = \varphi\left(\frac{kt}{T}\right).$$

Then, the system (4.2) can be rewritten as follows

$$(4.5) \quad \begin{cases} \partial_t \mathcal{V}_N + \mathcal{L}(\mathcal{V}_N + \psi_k) + \mathcal{B}(\mathcal{V}_N + \psi_k) = \mathbb{P}P_N f + \eta + f_k \\ \operatorname{div} \mathcal{V}_N = 0 \\ \mathcal{V}_N(0) = \mathcal{V}_0 = P_N \mathcal{U}_0, \end{cases}$$

where

$$(4.6) \quad f_k(t) = g_k(t) + h_k(t),$$

with

$$(4.7) \quad \begin{cases} g_k(t) = \mathcal{L}\psi_k(t) - \sum_{j=1}^m \lambda_j \mathcal{L}\rho^j \\ h_k(t) = \mathcal{B}(\mathcal{V}_N + \psi_k(t)) - \sum_{j=1}^m \lambda_j \mathcal{B}(\mathcal{V}_N + \rho^j). \end{cases}$$

We remark that, for any $s \in \{1, 2\}$ and for any $\mathcal{U} \in V^s(\mathbb{T}^2)^2$, we have

$$\|\mathcal{L}\mathcal{U}\|_{V^s(\mathbb{T}^2)^2} \leq \frac{\nu}{\alpha} \|\mathcal{U}\|_{V^s(\mathbb{T}^2)^2}.$$

Then, for $s \in \{1, 2\}$ and for any $t \geq 0$, simple calculations give,

$$(4.8) \quad \|g_k(t)\|_{V^s(\mathbb{T}^2)^2} \leq \|\mathcal{L}\psi_k(t)\|_{V^s(\mathbb{T}^2)^2} + \sum_{j=1}^m \lambda_j \|\mathcal{L}\rho^j\|_{V^s(\mathbb{T}^2)^2} \leq \frac{2\nu}{\alpha} \max_{1 \leq j \leq m} \|\rho^j\|_{V^s(\mathbb{T}^2)^2}$$

$$(4.9) \quad \begin{aligned} \|h_k(t)\|_{V^s(\mathbb{T}^2)^2} &\leq \|\mathcal{B}(\mathcal{V}_N + \psi_k(t))\|_{V^s(\mathbb{T}^2)^2} + \sum_{j=1}^m \lambda_j \|\mathcal{B}(\mathcal{V}_N + \rho^j)\|_{V^s(\mathbb{T}^2)^2} \\ &\leq 2 \max_{1 \leq j \leq m} \|\mathcal{B}(\mathcal{V}_N + \rho^j)\|_{V^s(\mathbb{T}^2)^2}. \end{aligned}$$

So, all we need to do now is to prove that, for any $\varepsilon > 0$, there exists $k_0 \in \mathbb{N}^*$ such that, for any $k \geq k_0$, we have

$$\|\mathcal{U}_k(T) - \bar{\mathcal{U}}(T)\|_{V^1(\mathbb{T}^2)^2} \leq \varepsilon,$$

where $\bar{\mathcal{U}}$ is the solution of the controlled system (1.6), with η replaced by $\bar{\eta} \in \mathcal{F}(E)$.

Recall that $\mathcal{W}_k = \mathcal{V}_N - \mathcal{K}f_k$. For any $t \geq 0$, we have

$$(4.16) \quad \begin{aligned} \|\mathcal{U}_k(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} &\leq \|\mathcal{U}_k(t) - \mathcal{V}_N(t)\|_{V^1(\mathbb{T}^2)^2} + \|\mathcal{V}_N(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} \\ &\leq \|\mathcal{U}_k(t) - \mathcal{W}_k(t)\|_{V^1(\mathbb{T}^2)^2} + \|\mathcal{K}f_k(t)\|_{V^1(\mathbb{T}^2)^2} + \|\mathcal{V}_N(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2}. \end{aligned}$$

Applying Theorem 2.1, we obtain

$$\|\mathcal{V}_N(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} \leq C \left(\|f - P_N f\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} + \|\mathcal{U}_0 - P_N \mathcal{U}_0\|_{V^1(\mathbb{T}^2)^2} \right) \leq C\delta.$$

and

$$\begin{aligned} \|\mathcal{U}_k(t) - \mathcal{W}_k(t)\|_{V^1(\mathbb{T}^2)^2} &\leq C \left(\|\mathcal{K}f_k\|_{L^2(0,T,V^2(\mathbb{T}^2)^2)} + \|\mathcal{B}(\psi_k + \mathcal{K}f_k) - \mathcal{B}(\psi_k)\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} \right. \\ &\quad \left. + \|f - P_N f\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} + \|\mathcal{U}_0 - P_N \mathcal{U}_0\|_{V^1(\mathbb{T}^2)^2} \right). \end{aligned}$$

Next, Estimate (4.10) implies that

$$\begin{aligned} \|\mathcal{B}(\psi_k + \mathcal{K}f_k) - \mathcal{B}(\psi_k)\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} &\leq \|\mathcal{B}(\psi_k, \mathcal{K}f_k)\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} + \|\mathcal{B}(\mathcal{K}f_k, \psi_k)\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} + \|\mathcal{B}(\mathcal{K}f_k)\|_{L^2(0,T,V^1(\mathbb{T}^2)^2)} \\ &\leq CT^{\frac{1}{2}} \|\mathcal{K}f_k\|_{L^\infty(0,T,V^2(\mathbb{T}^2)^2)} \left(\|\mathcal{K}f_k\|_{L^\infty(0,T,V^2(\mathbb{T}^2)^2)} + \max_{1 \leq j \leq m} \|\rho^j\|_{V^2(\mathbb{T}^2)^2} \right) \end{aligned}$$

Then, we deduce from (4.16) that

$$\begin{aligned} \|\mathcal{U}_k(t) - \bar{\mathcal{U}}(t)\|_{V^1(\mathbb{T}^2)^2} &\leq C\delta + CT^{\frac{1}{2}} \|\mathcal{K}f_k\|_{L^\infty(0,T,V^2(\mathbb{T}^2)^2)} \left(\|\mathcal{K}f_k\|_{L^\infty(0,T,V^2(\mathbb{T}^2)^2)} + \max_{1 \leq j \leq m} \|\rho^j\|_{V^2(\mathbb{T}^2)^2} + 1 \right). \end{aligned}$$

Now, we choose $\delta > 0$ such that $C\delta \leq \frac{\varepsilon}{2}$. In order to prove Theorem 4.1, we only need to prove the following lemma.

Lemma 4.5. *We have*

$$\lim_{k \rightarrow +\infty} \|\mathcal{K}f_k\|_{L^\infty(0,T,V^2(\mathbb{T}^2)^2)} = 0.$$

In order to prove Lemma 4.5, we need to prove the following result for f_k .

Lemma 4.6. *Let $T > 0$ and for any $k \in \mathbb{N}^*$, let f_k be defined as in (4.6). Then, we have*

$$\lim_{k \rightarrow +\infty} \sup_{t \in [0,T]} \left\| \int_0^t f_k(s) ds \right\|_{V^2(\mathbb{T}^2)^2} = 0.$$

Step 3. *Proof of Lemma 4.6.*

For any $k \in \mathbb{N}^*$ and for any $t > 0$, let

$$F_k(t) = \int_0^t f_k(s) ds.$$

So, our goal is to prove that

$$(4.17) \quad \lim_{k \rightarrow +\infty} \|F_k\|_{C(0,T,V^2(\mathbb{T}^2)^2)} = 0.$$

We remark that Estimates (4.11), (4.12), (4.13) and the definition of f_k imply that if (4.17) is true for all piecewise constant (with respect to the time variable) functions \mathcal{V}_N , then (4.17) is true for all functions \mathcal{V}_N (by using an approximation of \mathcal{V}_N by piecewise constant functions). For this reason, we suppose that there exist $L \in \mathbb{N}^*$, $t_0, \dots, t_L \in \mathbb{R}_+$ such that

$$0 = t_0 < \dots < t_L = T,$$

and that

$$\mathcal{V}_N(t) = v_q, \quad \forall t \in]t_{q-1}, t_q], \quad \forall q \in \{1, \dots, L\}.$$

Now, by using direct calculations, we can prove that

$$\lim_{k \rightarrow +\infty} F_k(t) = 0.$$

For the details, we send the reader to the book of Jurdjevic [19]. We remark that, for any $t \in [0, T]$, the set $\{F_k(t)\}_k$ is relatively compact in $V^2(\mathbb{T}^2)^2$. Indeed, the set $\{f_k(t)\}$ only takes a finite number of values, independently of k . Let M be the set of value of $\{f_k(t)\}$ and we suppose that

$$M = \{M_1, \dots, M_K\}, \quad K \in \mathbb{N}^*.$$

Then, there exist positive constant a_1, \dots, a_K such that

$$a_1 + \dots + a_K = t$$

and

$$F_k(t) = \sum_{i=1}^K a_i M_i.$$

Thus, $\{F_k(t)\}_k$ is relatively compact in $V^2(\mathbb{T}^2)^2$. Moreover, from (4.12) and (4.13), there exists a positive constant C_0 such that

$$\sup_{t \in [0, T]} \|f_k(t)\|_{V^2(\mathbb{T}^2)^2} \leq C_0,$$

which means that $\{F_k(\cdot)\}_k$ is equicontinuous. Then, the Ascoli's theorem implies that $\{F_k(\cdot)\}_k$ is relatively compact in $C(0, T, V^2(\mathbb{T}^2)^2)$.

Next, we have

- $\{F_k(\cdot)\}_k$ is relatively compact in $C(0, T, V^2(\mathbb{T}^2)^2)$.
- $F_k(t) \rightarrow 0$ in $V^2(\mathbb{T}^2)^2$, for any $t \in [0, T]$.

Then, it is clear that

$$\lim_{k \rightarrow +\infty} \sup_{t \in [0, T]} \|F_k(t)\|_{V^2(\mathbb{T}^2)^2} = \lim_{k \rightarrow +\infty} \sup_{t \in [0, T]} \left\| \int_0^t f_k(s) ds \right\|_{V^2(\mathbb{T}^2)^2} = 0. \quad \blacksquare$$

Step 4. *Proof of Lemma 4.5.*

We recall that $\mathcal{Z} = \mathcal{K}f_k$ is the solution of the system

$$(4.18) \quad \begin{cases} \partial_t \mathcal{Z} + \mathcal{L}\mathcal{Z} = \mathbb{P}f_k \\ \operatorname{div} \mathcal{Z} = 0 \\ \mathcal{Z}(0) = 0. \end{cases}$$

or equivalently, $z = (I - \alpha\Delta)^{-1} \mathcal{Z}$ is solution of the system

$$(4.19) \quad \begin{cases} \partial_t(z - \alpha\Delta z) - \nu\Delta z = \mathbb{P}f_k \\ \operatorname{div} z = 0 \\ z(0) = 0. \end{cases}$$

We also recall that *a priori* estimates in this paragraph can be justified by applying an approximation by a Galerkin scheme. Following the method presented in [24], we apply the *rot* operator to the first equation of (4.19) and then we take the L^2 scalar product of the obtained equation with $-\text{rot}(\Delta z - \alpha \Delta^2 z)$. We get

$$(4.20) \quad \frac{1}{2} \frac{d}{dt} \|\nabla(\text{rot } z - \alpha \text{rot } \Delta z)\|_{L^2(\mathbb{T}^2)^2}^2 + \nu \left(\|\Delta \text{rot } z\|_{L^2(\mathbb{T}^2)^2}^2 + \alpha \|\Delta^2 z\|_{L^2(\mathbb{T}^2)^2}^2 \right) \\ = - \langle \text{rot } f_k, \text{rot}(\Delta z - \alpha \Delta^2 z) \rangle_{L^2(\mathbb{T}^2)^2}.$$

Integrating over $[0, t]$ and then, performing multiple integrations by parts (with respect to the space variable x and then with respect to the time variable t), we have

$$(4.21) \quad \frac{1}{2} \|\nabla(\text{rot } z(t) - \alpha \text{rot } \Delta z(t))\|_{L^2(\mathbb{T}^2)^2}^2 + \nu \left(\int_0^t \|\Delta \text{rot } z(s)\|_{L^2(\mathbb{T}^2)^2}^2 ds + \alpha \int_0^t \|\Delta^2 z(s)\|_{L^2(\mathbb{T}^2)^2}^2 ds \right) \\ = - \int_0^t \int_{\mathbb{T}^2} \text{rot } f_k(s, x) \cdot \text{rot}(\Delta z - \alpha \Delta^2 z)(s, x) dx ds \\ = \int_0^t \int_{\mathbb{T}^2} \nabla \text{rot } f_k(s, x) : \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(s, x) dx dt \\ = \int_{\mathbb{T}^2} \left(\int_0^t \nabla \text{rot } f_k(s, x) ds \right) : \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(t, x) dx \\ \quad - \int_{\mathbb{T}^2} \int_0^t \left(\int_0^s \nabla \text{rot } f_k(\tau, x) d\tau \right) : \left(\frac{\partial}{\partial s} \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(s, x) \right) ds dx \\ = J_1(t, k) + J_2(t, k).$$

For the first term on the right-hand side, Cauchy-Schwarz inequality implies that

$$(4.22) \quad |J_1(t, k)| \leq \left\| \int_0^t \nabla \text{rot } f_k(s, x) ds \right\|_{L^2(\mathbb{T}^2)^2} \|\nabla(\text{rot } z(t) - \alpha \text{rot } \Delta z(t))\|_{L^2(\mathbb{T}^2)^2} \\ \leq C \left\| \int_0^t f_k(s, x) ds \right\|_{V^2(\mathbb{T}^2)^2} \|\nabla(\text{rot } z(t) - \alpha \text{rot } \Delta z(t))\|_{L^2(\mathbb{T}^2)^2}.$$

For the second term, also using Cauchy-Schwarz inequality, we obtain

$$|J_2(t, k)| \leq \int_0^t \left(\left\| \int_0^s \nabla \text{rot } f_k(\tau) d\tau \right\|_{L^2(\mathbb{T}^2)^2} \left\| \frac{\partial}{\partial s} \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(s) \right\|_{L^2(\mathbb{T}^2)^2} \right) ds \\ \leq \left(\int_0^t \left\| \int_0^s f_k(\tau) d\tau \right\|_{V^2(\mathbb{T}^2)^2}^2 ds \right)^{\frac{1}{2}} \left(\int_0^t \left\| \frac{\partial}{\partial s} \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(s) \right\|_{L^2(\mathbb{T}^2)^2}^2 ds \right)^{\frac{1}{2}} \\ \leq T^{\frac{1}{2}} \sup_{t \in [0, T]} \left\| \int_0^t f_k(s) ds \right\|_{V^2(\mathbb{T}^2)^2} \left(\int_0^t \left\| \frac{\partial}{\partial s} \nabla(\text{rot } z - \alpha \text{rot } \Delta z)(s) \right\|_{L^2(\mathbb{T}^2)^2}^2 ds \right)^{\frac{1}{2}}.$$

Now, we come back the first equation of (4.19). Applying the *rot* operator to this equation and then, taking the L^2 scalar product of the obtained equation with $-\frac{\partial}{\partial t} \text{rot}(\Delta z - \alpha \Delta^2 z)$, we get

$$\|\partial_t \nabla \text{rot}(z - \alpha \Delta z)\|_{L^2(\mathbb{T}^2)^2}^2 + \frac{\nu}{2} \frac{d}{dt} \left(\|\text{rot } \Delta z\|_{L^2(\mathbb{T}^2)^2}^2 + \alpha \|\Delta^2 z\|_{L^2(\mathbb{T}^2)^2}^2 \right) \\ = \langle \nabla \text{rot } f_k, \partial_t \nabla \text{rot}(z - \alpha \Delta z) \rangle_{L^2(\mathbb{T}^2)^2}.$$

Thus,

$$\begin{aligned} & \int_0^t \|\partial_s \nabla \operatorname{rot} (z(s) - \alpha \Delta z(s))\|_{L^2(\mathbb{T}^2)^2}^2 ds + \frac{\nu}{2} \left(\|\operatorname{rot} \Delta z(t)\|_{L^2(\mathbb{T}^2)^2}^2 + \alpha \|\Delta^2 z(t)\|_{L^2(\mathbb{T}^2)^2}^2 \right) \\ & \leq \int_0^t \|\nabla \operatorname{rot} f_k(s)\|_{L^2(\mathbb{T}^2)^2} \|\partial_s \nabla \operatorname{rot} (z(s) - \alpha \Delta z(s))\|_{L^2(\mathbb{T}^2)^2} ds \\ & \leq \|f_k\|_{L^2(0,T,V^2(\mathbb{T}^2)^2)} \left(\int_0^t \|\partial_s \nabla \operatorname{rot} (z(s) - \alpha \Delta z(s))\|_{L^2(\mathbb{T}^2)^2}^2 ds \right)^{\frac{1}{2}} \end{aligned}$$

Come back to $J_2(t, k)$, we have

$$(4.23) \quad |J_2(t, k)| \leq CT \sup_{t \in [0, T]} \left\| \int_0^t f_k(s) ds \right\|_{V^2(\mathbb{T}^2)^2} \|f_k\|_{L^\infty(0, T, V^2(\mathbb{T}^2)^2)}.$$

Combining (4.21) with (4.22), (4.23) and the fact that

$$\lim_{k \rightarrow +\infty} \sup_{t \in [0, T]} \left\| \int_0^t f_k(s) ds \right\|_{V^2(\mathbb{T}^2)^2} = 0,$$

we conclude that

$$0 \leq \lim_{k \rightarrow +\infty} \|\mathcal{K}f_k\|_{L^\infty(0, T, V^2(\mathbb{T}^2)^2)} \leq C \lim_{k \rightarrow +\infty} \|\nabla (\operatorname{rot} z(t) - \alpha \operatorname{rot} \Delta z(t))\|_{L^\infty(0, T, L^2(\mathbb{T}^2)^2)} = 0. \quad \blacksquare$$

5. SATURATION PROPERTY FOR THE CONTROLLED SYSTEM OF FLUIDS OF SECOND GRADE

Let $q = (q_1, q_2) \in]0, +\infty[^2$ be fixed and

$$\mathbb{T}_q^2 = \mathbb{R}^2 / \mathbb{Z}_q^2 \quad \text{with} \quad \mathbb{Z}_q^2 = \left\{ x = (x_1, x_2) \in \mathbb{R}^2 \mid \frac{x_i}{q_i} \in \mathbb{Z}, i = 1, 2 \right\}.$$

For any $x = (x_1, x_2), y = (y_1, y_2) \in \mathbb{R}^2$, let

$$\langle x, y \rangle = x_1 y_1 + x_2 y_2, \quad |x| = |x_1| + |x_2|, \quad \|x\| = \sqrt{\langle x, x \rangle},$$

and

$$\langle x, y \rangle_q = \frac{x_1 y_1}{q_1} + \frac{x_2 y_2}{q_2}, \quad \|x\|_q = \sqrt{\frac{x_1^2}{q_1^2} + \frac{x_2^2}{q_2^2}}.$$

For any $a = (a_1, a_2) \in \mathbb{R}^2 \setminus \{0\}$, let $a^\perp = (-a_2, a_1)$. We will denote $a^{q,\perp}$ the unit vector which satisfied $\langle a, a^{q,\perp} \rangle_q = 0$ and $\|a^{q,\perp}\| = 1$ and we denote P_a the orthogonal of \mathbb{R}^2 onto the subspace $\operatorname{Span} \{a^{q,\perp}\}$ generated by $a^{q,\perp}$. Direct calculations also give

Lemma 5.1. *Let $a, l \in \mathbb{R}^2 \setminus \{0\}$. Then,*

$$(5.1) \quad \mathbb{P} \left(a \cos \langle l, x \rangle_q \right) = (P_l a) \cos \langle l, x \rangle_q$$

$$(5.2) \quad \mathbb{P} \left(a \sin \langle l, x \rangle_q \right) = (P_l a) \sin \langle l, x \rangle_q$$

We recall that for any $m \in \mathbb{Z}^2 \setminus \{0\}$, we set

$$c_m(x) = m^{q,\perp} \cos \langle m, x \rangle_q \quad \text{and} \quad s_m(x) = m^{q,\perp} \sin \langle m, x \rangle_q.$$

These vector fields c_m, s_m , with $m \in \mathbb{Z}^2 \setminus \{0\}$, are eigenvectors of the Stokes operator $-\mathbb{P}\Delta$ and the family $\{c_m, s_m \mid m \in \mathbb{Z}^2 \setminus \{0\}\}$ forms an orthonormal basis of $V^k(\mathbb{T}_q^2)^2$, $k \in \mathbb{N}$. In Section 1, for any $N \in \mathbb{N}^*$, we already set

$$(1.5) \quad \mathcal{H}_q^N = \operatorname{Span} \{c_m, s_m \mid m \in \mathbb{Z} \setminus \{0\}, |m| \leq N\}.$$

For any $m \in \mathbb{Z}^2 \setminus \{0\}$, let

$$\mathcal{C}_m = \text{Span} \{c_m, c_{-m}\} \quad \text{and} \quad \mathcal{S}_m = \text{Span} \{s_m, s_{-m}\}.$$

Lemma 5.2. *Let $m, n \in \mathbb{Z}^2 \setminus \{0\}$. For any $f_m \in \mathcal{C}_m$ and $g_n \in \mathcal{S}_n$, there exist $\tilde{f}_m, \tilde{g}_n \in \mathbb{R}^2$ such that*

$$\begin{aligned} \langle \tilde{f}_m, m \rangle_q &= \langle \tilde{g}_n, n \rangle_q = 0, \\ f_m(x) &= \tilde{f}_m \cos \langle m, x \rangle_q, \\ g_n(x) &= \tilde{g}_n \sin \langle n, x \rangle_q. \end{aligned}$$

For any $m, n \in \mathbb{Z}^2 \setminus \{0\}$ and for any $f_m \in \mathcal{C}_m$ and $g_n \in \mathcal{S}_n$, Lemma 5.2 allows to calculate

$$\begin{aligned} &\mathbb{P}(\text{rot } f_m \times ((I - \alpha\Delta)^{-1}g_n)) \\ &= \mathbb{P} \left\{ \left(\nabla \times \left(\tilde{f}_m \cos \langle m, x \rangle_q \right) \right) \times \left((Id - \alpha\Delta)^{-1} \left(\tilde{g}_n \sin \langle n, x \rangle_q \right) \right) \right\} \\ &= \mathbb{P} \left\{ \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left[\nabla \times \left(\tilde{f}_m \cos \langle m, x \rangle_q \right) \right] \times \left(\tilde{g}_n \sin \langle n, x \rangle_q \right) \right\} \\ &= \left(1 + \alpha \|n\|_q^2 \right)^{-1} \mathbb{P} \left\{ \left(\langle \tilde{f}_m^\perp, m \rangle_q \sin \langle m, x \rangle_q \right) \times \left(\tilde{g}_n \sin \langle n, x \rangle_q \right) \right\} \\ &= \left(1 + \alpha \|n\|_q^2 \right)^{-1} \langle \tilde{f}_m^\perp, m \rangle_q \mathbb{P} \left(\tilde{g}_n^\perp \sin \langle m, x \rangle_q \sin \langle n, x \rangle_q \right) \\ &= \frac{\left(1 + \alpha \|n\|_q^2 \right)^{-1}}{2} \langle \tilde{f}_m^\perp, m \rangle_q \mathbb{P} \left[\tilde{g}_n^\perp \left(\cos \langle m - n, x \rangle_q - \cos \langle m + n, x \rangle_q \right) \right]. \end{aligned}$$

Using Lemma 5.1, we obtain

$$\begin{aligned} (5.3) \quad \mathcal{B}(f_m, g_n) &= \mathbb{P}(\text{rot } f_m \times ((I - \alpha\Delta)^{-1}g_n)) \\ &= \frac{\left(1 + \alpha \|n\|_q^2 \right)^{-1}}{2} \langle \tilde{f}_m^\perp, m \rangle_q \left(\cos \langle m - n, x \rangle_q P_{m-n} - \cos \langle m + n, x \rangle_q P_{m+n} \right) \tilde{g}_n^\perp. \end{aligned}$$

Similar calculations give

$$(5.4) \quad \mathcal{B}(g_m, f_n) = - \frac{\left(1 + \alpha \|n\|_q^2 \right)^{-1}}{2} \langle \tilde{g}_m^\perp, m \rangle_q \left(\cos \langle m + n, x \rangle_q P_{m+n} + \cos \langle m - n, x \rangle_q P_{m-n} \right) \tilde{f}_n^\perp,$$

$$(5.5) \quad \mathcal{B}(f_m, f_n) = \frac{\left(1 + \alpha \|n\|_q^2 \right)^{-1}}{2} \langle \tilde{f}_m^\perp, m \rangle_q \left(\sin \langle m + n, x \rangle_q P_{m+n} + \sin \langle m - n, x \rangle_q P_{m-n} \right) \tilde{f}_n^\perp,$$

and

$$(5.6) \quad \mathcal{B}(g_m, g_n) = \frac{\left(1 + \alpha \|n\|_q^2 \right)^{-1}}{2} \langle \tilde{g}_m^\perp, m \rangle_q \left(\sin \langle m - n, x \rangle_q P_{m-n} - \sin \langle m + n, x \rangle_q P_{m+n} \right) \tilde{g}_n^\perp.$$

The next lemma is the most important result of this section, which allows us to prove the saturation property of the space of controls (Theorem 1.8).

Lemma 5.3. *Let $q = (q_1, q_2)$, $q_1, q_2 > 0$. For any $m, n \in \mathbb{Z}^2 \setminus \{0\}$ satisfying*

- $\|m\|_q \neq \|n\|_q$,
- m, n are not parallel,

and for any $f \in \mathcal{C}_{m+n}$, $g \in \mathcal{S}_{m+n}$, there exist

$$a, b \in \text{Span} \{ \mathcal{C}_m, \mathcal{C}_n, \mathcal{S}_m, \mathcal{S}_n \}$$

such that

$$(5.7) \quad \mathcal{B}(a) + f, \mathcal{B}(b) + g \in \text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \},$$

where \mathcal{B} is defined in (1.7).

Proof. Taking $m = n$ in Estimates (5.5) and (5.6), we have

$$(5.8) \quad \mathcal{B}(f_m, f_m) = \frac{1}{2} \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \sin \langle 2m, x \rangle_q P_{2m} \tilde{f}_m^\perp,$$

$$(5.9) \quad \mathcal{B}(g_m, g_m) = -\frac{1}{2} \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_m^\perp, m \right\rangle_q \sin \langle 2m, x \rangle_q P_{2m} \tilde{g}_m^\perp.$$

Since $\left\langle \tilde{f}_m, m \right\rangle_q = \left\langle \tilde{g}_m, m \right\rangle_q = 0$, we deduce that $\tilde{f}_m, \tilde{g}_m \in \text{Span} \{ m_q^\perp \}$. By definition, P_{2m} is the projection onto the subspace $\text{Span} \{ (2m)_q^\perp \} = \text{Span} \{ m_q^\perp \}$. So, we have

$$P_{2m} \left(\tilde{f}_m^\perp \right) = P_{2m} \left(\tilde{g}_m^\perp \right) = 0,$$

which means that, for any $m \in \mathbb{Z}^2 \setminus \{0\}$,

$$(5.10) \quad \mathcal{B}(f_m, f_m) = \mathcal{B}(g_m, g_m) = 0.$$

Now, following the idea of [26], for any $f \in \mathcal{C}_{m+n}$, we look for $a \in \text{Span} \{ \mathcal{C}_m, \mathcal{S}_n \}$ under the form

$$(5.11) \quad a = f_m + g_n, \quad f_m \in \mathcal{C}_m, \quad g_n \in \mathcal{S}_n,$$

such that

$$\mathcal{B}(a) + f \in \text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \}.$$

Since $a = f_m + g_n$, taking into account (5.3), (5.4) and (5.10), we have

$$\begin{aligned} \mathcal{B}(a) &= \frac{1}{2} \cos \langle m - n, x \rangle_q P_{m-n} \left\{ \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \tilde{g}_n^\perp - \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_n^\perp, n \right\rangle_q \tilde{f}_m^\perp \right\} \\ &\quad - \frac{1}{2} \cos \langle m + n, x \rangle_q P_{m+n} \left\{ \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \tilde{g}_n^\perp + \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_n^\perp, n \right\rangle_q \tilde{f}_m^\perp \right\}. \end{aligned}$$

We remark that

$$\cos \langle m - n, x \rangle_q P_{m-n} \left\{ \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \tilde{g}_n^\perp - \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_n^\perp, n \right\rangle_q \tilde{f}_m^\perp \right\}$$

belongs to $\text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \}$. So, we only need to prove that, for any $f \in \mathcal{C}_{m+n}$, there are $f_m \in \mathcal{C}_m$ and $g_n \in \mathcal{S}_n$ such that

$$(5.12) \quad f = \frac{1}{2} \cos \langle m + n, x \rangle_q P_{m+n} \left\{ \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \tilde{g}_n^\perp + \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_n^\perp, n \right\rangle_q \tilde{f}_m^\perp \right\}.$$

Let

$$F = \left(1 + \alpha \|n\|_q^2 \right)^{-1} \left\langle \tilde{f}_m^\perp, m \right\rangle_q \tilde{g}_n^\perp + \left(1 + \alpha \|m\|_q^2 \right)^{-1} \left\langle \tilde{g}_n^\perp, n \right\rangle_q \tilde{f}_m^\perp.$$

Then, we will prove (5.12) if we can find $f_m \in \mathcal{C}_m$ and $g_n \in \mathcal{S}_n$ such that $P_{m+n} F \neq 0$, or equivalently, $\langle F, G \rangle \neq 0$, for some vector $G \neq 0$ and $G \in \text{Span} \{ (m+n)_q^\perp \}$. For the sake of simplicity, we choose

$$G = ((m_2 + n_2)q_1, -(m_1 + n_1)q_2).$$

For any $f_m \in \mathcal{C}_m$ and $g_n \in \mathcal{S}_n$, recall that $\langle \tilde{f}_m, m \rangle_q = \langle \tilde{g}_n, n \rangle_q = 0$. Thus, there exist $C_f, C_g \in \mathbb{R}$ such that

$$\tilde{f}_m = C_f (m_2 q_1, -m_1 q_2) \quad \text{and} \quad \tilde{g}_n = C_g (n_2 q_1, -n_1 q_2)$$

We get

$$\tilde{f}_m^\perp = C_f (m_1 q_2, m_2 q_1) \quad \text{and} \quad \tilde{g}_n^\perp = C_g (n_1 q_2, n_2 q_1),$$

and

$$\begin{aligned} \langle \tilde{f}_m^\perp, m \rangle_q &= \frac{q_2}{q_1} m_1^2 + \frac{q_1}{q_2} m_2^2 = q_1 q_2 \|m\|_q^2 \\ \langle \tilde{g}_n^\perp, n \rangle_q &= \frac{q_2}{q_1} n_1^2 + \frac{q_1}{q_2} n_2^2 = q_1 q_2 \|n\|_q^2. \end{aligned}$$

Let

$$C = \left(1 + \alpha \|m\|_q^2\right) \left(1 + \alpha \|n\|_q^2\right).$$

Then,

$$F = CC_f C_g q_1 q_2 \left[\left(1 + \alpha \|m\|_q^2\right) \|m\|_q^2 (n_1 q_2, n_2 q_1) + \left(1 + \alpha \|n\|_q^2\right) \|n\|_q^2 (m_1 q_2, m_2 q_1) \right],$$

Let

$$M_q = \left(1 + \alpha \|m\|_q^2\right) \|m\|_q^2 \quad \text{and} \quad N_q = \left(1 + \alpha \|n\|_q^2\right) \|n\|_q^2.$$

Since $\|m\|_q \neq \|n\|_q$ and m, n are not parallel in \mathbb{R}^2 , we finally obtain

$$\begin{aligned} \langle F, G \rangle &= CC_f C_g q_1^2 q_2^2 [(M_q n_1 q_2 + N_q m_1 q_2) (m_2 q_1 + n_2 q_1) - (M_q n_2 q_1 + N_q m_2 q_1) (m_1 q_2 + n_1 q_2)] \\ &= CC_f C_g q_1^2 q_2^2 (M_q - N_q) (n_1 m_2 - n_2 m_1) \neq 0, \end{aligned}$$

if f_m and g_n are not zero.

To prove the second part of the lemma, for any $g \in \mathcal{S}_{m+n}$, we can look for b under the form

$$b = f_m + f_n \quad \text{or} \quad b = g_m + g_n,$$

where $f_m \in \mathcal{C}_m$, $f_n \in \mathcal{C}_n$, $g_m \in \mathcal{S}_m$ and $g_n \in \mathcal{S}_n$. Indeed, taking into account (5.5), (5.6) and (5.10), we have

$\mathcal{B}(f_m + f_n)$

$$\begin{aligned} &= \frac{1}{2} \sin \langle m - n, x \rangle_q P_{m-n} \left\{ \left(1 + \alpha \|n\|_q^2\right)^{-1} \langle \tilde{f}_m^\perp, m \rangle_q \tilde{f}_n^\perp - \left(1 + \alpha \|m\|_q^2\right)^{-1} \langle \tilde{f}_n^\perp, n \rangle_q \tilde{f}_m^\perp \right\} \\ &\quad + \frac{1}{2} \sin \langle m + n, x \rangle_q P_{m+n} \left\{ \left(1 + \alpha \|n\|_q^2\right)^{-1} \langle \tilde{f}_m^\perp, m \rangle_q \tilde{f}_n^\perp + \left(1 + \alpha \|m\|_q^2\right)^{-1} \langle \tilde{f}_n^\perp, n \rangle_q \tilde{f}_m^\perp \right\}, \end{aligned}$$

and

$\mathcal{B}(g_m + g_n)$

$$\begin{aligned} &= \frac{1}{2} \sin \langle m - n, x \rangle_q P_{m-n} \left\{ \left(1 + \alpha \|n\|_q^2\right)^{-1} \langle \tilde{g}_m^\perp, m \rangle_q \tilde{g}_n^\perp - \left(1 + \alpha \|m\|_q^2\right)^{-1} \langle \tilde{g}_n^\perp, n \rangle_q \tilde{g}_m^\perp \right\} \\ &\quad - \frac{1}{2} \sin \langle m + n, x \rangle_q P_{m+n} \left\{ \left(1 + \alpha \|n\|_q^2\right)^{-1} \langle \tilde{g}_m^\perp, m \rangle_q \tilde{g}_n^\perp + \left(1 + \alpha \|m\|_q^2\right)^{-1} \langle \tilde{g}_n^\perp, n \rangle_q \tilde{g}_m^\perp \right\}. \end{aligned}$$

Then, we can repeat the above argument for a to find b . Lemma 5.3 is proved. \blacksquare

In what follows, we recall that, for any finite-dimensional subspace E of $V^3(\mathbb{T}^2)^2$, we have defined $\mathcal{F}(E)$ as the largest vector subspace of $V^3(\mathbb{T}^2)^2$ such that, for any $\bar{\eta} \in \mathcal{F}(E)$, there exist

$$k \in \mathbb{N}^*; \alpha_1, \dots, \alpha_k > 0; \eta, \rho^1, \dots, \rho^k \in E$$

satisfying

$$\bar{\eta} = \eta - \sum_{j=1}^k \alpha_j \mathcal{B}(\rho^j).$$

We have also defined a sequence of subspace

$$E = E_0 \subset E_1 \subset \dots \subset E_n \subset \dots$$

such that, for any $n \in \mathbb{N}$ we have $E_{n+1} = \mathcal{F}(E_n)$ and we set

$$E_\infty = \bigcup_{n=0}^{\infty} E_n.$$

The saturation property in Theorem 1.8 can be made precise as follows

Theorem 5.4 (Saturation Property). *Let $q = (q_1, q_2)$, $q_1, q_2 > 0$, let E be a finite-dimensional subspace of $V^3(\mathbb{T}^2)^2$ and for any $N \in \mathbb{N}^*$, let \mathcal{H}_q^N be defined as in (1.5). If $E \supset \mathcal{H}_q^3$, then $E_\infty \supset \mathcal{H}_q^N$, for any $N \in \mathbb{N}$, $N \geq 3$.*

Proof. Inspired by the argument of [[26], Theorem 2.5], we will prove Theorem 5.4 by recurrence that, if $E = E_0 \supset \mathcal{H}_q^3$ then, for any $k \geq 0$, we have

$$(5.13) \quad E_{2k} \supset \mathcal{H}_q^{k+3}.$$

It is evident that for $k = 0$, (5.13) is true. Let $k \geq 1$. We suppose that, for any $k' \in \mathbb{N}$, $0 \leq k' < k$, we have $E_{2k'} \supset \mathcal{H}_q^{k'+3}$. In order to prove that (5.13) is true for k , we only need to prove that, for any $l \in \mathbb{Z}^2 \setminus \{0\}$, $|l| = k + 3$, we have $c_l, s_l \in E_{2k}$.

1. First case: If $l = (l_1, l_2)$ with $l_1 \neq 0$ and $l_2 \neq 0$. In this case, since $|l_1| + |l_2| > 3$, without loss of generality, we can suppose that $l_1 \geq 2$. We choose $m = (l_1 - 1, l_2)$ and $n = (1, 0)$. Then, we have

$$m + n = l, \quad \|m\|_q > \|n\|_q, \quad |m| = k + 2, \quad |n| = 1, \quad |m - n| = k + 1$$

and m, n are not parallel in \mathbb{R}^2 . Applying Lemma 5.3, we obtain the existence of

$$a, b \in \text{Span} \{ \mathcal{C}_m, \mathcal{C}_n, \mathcal{S}_m, \mathcal{S}_n \} \subset \mathcal{H}_q^{k+2} \subset E_{2k-2}$$

such that

$$\mathcal{B}(a) + c_l, \mathcal{B}(b) + s_l \in \text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \}.$$

Thus, there exist

$$f, g \in \text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \} \subset \mathcal{H}_q^{k+1} \subset E_{2k-2}$$

such that

$$c_l = f - \mathcal{B}(a), \quad s_l = g - \mathcal{B}(b).$$

Then, using the definition of $E_{2k-1} = \mathcal{F}(E_{2k-2})$, we deduce that

$$c_l, s_l \in E_{2k-1} \subset E_{2k}.$$

2. Second case: If $l = (l_1, l_2)$ with $l_1 = |l| = 3$ and $l_2 = 0$. In this case, we choose $m = (l_1 - 1, 1)$ and $n = (1, -1)$. Then, we have

$$m + n = l, \quad \|m\|_q > \|n\|_q, \quad |m| = k + 3, \quad |n| = 2, \quad |m - n| = k + 3$$

and m, n are not parallel in \mathbb{R}^2 . Since all the components of the vectors $m, n, m - n$ are not zero, we can apply the result of the first case and we deduce that

$$\text{Span} \{ \mathcal{C}_m, \mathcal{C}_n, \mathcal{S}_m, \mathcal{S}_n \} \subset E_{2k-1}$$

and

$$\text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \} \subset E_{2k-1}.$$

Now, applying Lemma 5.3, we obtain the existence of

$$a, b \in \text{Span} \{ \mathcal{C}_m, \mathcal{C}_n, \mathcal{S}_m, \mathcal{S}_n \} \subset E_{2k-1}$$

such that

$$\mathcal{B}(a) + c_l, \mathcal{B}(b) + s_l \in \text{Span} \{ \mathcal{C}_{m-n}, \mathcal{S}_{m-n} \} \subset E_{2k-1}.$$

As in the first case, we can deduce that

$$c_l, s_l \in \mathcal{F}(E_{2k-1}) = E_{2k}.$$

Theorem 5.4 is proved. \blacksquare

6. APPROXIMATE CONTROLLABILITY BY HIGH-MODE CONTROLS REDUCED TO APPROXIMATE CONTROLLABILITY BY LOW-MODE CONTROLS

The goal of this section is to prove the main theorem 1.4 by proving that we can reduce the control of the system (1.1) by high-mode controls to controls in \mathcal{H}_q^3 . Let $T > 0$, $\varepsilon > 0$ and $u_0, u_T \in V^4(\mathbb{T}^2)^2$. We set

$$\mathcal{U}_0 = u_0 - \alpha \Delta u_0 \quad \text{and} \quad \mathcal{U}_T = u_T - \alpha \Delta u_T.$$

For any $t \in [0, T]$, let

$$\bar{\mathcal{U}}(t) = \frac{1}{T} (I - \alpha \Delta) ((T - t)u_0 + tu_T).$$

Then, $\bar{\mathcal{U}}$ is solution of the system (1.6) with

$$\bar{\mathcal{U}}(0) = \mathcal{U}_0 \quad \text{and} \quad \eta = \partial_t \bar{\mathcal{U}} + \mathcal{L}\bar{\mathcal{U}} + \mathcal{B}(\bar{\mathcal{U}}) - \mathbb{P}f.$$

It is clear that

$$\bar{\mathcal{U}} \in C(0, T, V^2(\mathbb{T}^2)^2) \quad \text{and} \quad \eta \in L^\infty(0, T, V^1(\mathbb{T}^2)^2).$$

Let $k \in \mathbb{N}^*$, $k \geq 3$ and let

$$\eta_k = P_k (\partial_t \bar{\mathcal{U}} + \mathcal{L}\bar{\mathcal{U}} + \mathcal{B}(\bar{\mathcal{U}}) - \mathbb{P}f),$$

where P_k is the projection onto \mathcal{H}_q^k . Let $\bar{\mathcal{U}}_k$ be the solution of the system (1.6) with

$$\bar{\mathcal{U}}_k(0) = \mathcal{U}_0 \quad \text{and} \quad \eta = \eta_k.$$

Applying Theorem 2.1, we can choose k so large that

$$\|\bar{\mathcal{U}}_k(T) - \bar{\mathcal{U}}(T)\|_{V^1(\mathbb{T}^2)^2} \leq C \|\eta_k - (\partial_t \bar{\mathcal{U}} + \mathcal{L}\bar{\mathcal{U}} + \mathcal{B}(\bar{\mathcal{U}}) - \mathbb{P}f)\|_{L^2(0, T, V^1(\mathbb{T}^2)^2)} \leq \varepsilon.$$

Now, Theorem 5.4 (see (5.13)) implies that $\mathcal{H}_q^k \subset E_N$, where $N = 2(k - 3)$. Now, we set $\mathcal{U}^N = \bar{\mathcal{U}}_k$. Applying Theorems 4.1 and 3.1, we can construct a sequence of controls $\eta_j \in E_j$, $j \in \{0, \dots, N\}$, and a sequence of solutions \mathcal{U}^j of the system (1.6) with

$$\mathcal{U}^j(0) = \mathcal{U}_0 \quad \text{and} \quad \eta = \eta_j,$$

such that

$$\|\mathcal{U}^{j-1}(T) - \mathcal{U}^j(T)\|_{V^1(\mathbb{T}^2)^2} \leq \frac{\varepsilon}{2^{N-j}},$$

for any $j \in \{1, \dots, N\}$. Thus, \mathcal{U}^0 is the solution of the system (1.6) with

$$\mathcal{U}^0(0) = \mathcal{U}_0 \quad \text{and} \quad \eta = \eta_0 \in E_0 = \mathcal{H}_q^3,$$

and moreover, we have

$$\|\mathcal{U}^0(T) - \mathcal{U}_T\|_{V^1(\mathbb{T}^2)^2} \leq \varepsilon + \sum_{j=1}^N \frac{\varepsilon}{2^{N-j}} < 3\varepsilon.$$

Finally, we set $u = (I - \alpha \Delta)^{-1} \mathcal{U}^0$. Then u is the solution of the system (1.1), with

$$u(0) = u_0 \quad \text{and} \quad \eta = \eta_0 \in \mathcal{H}_q^3.$$

Moreover, we have

$$\|u(T) - u_T\|_{V^3(\mathbb{T}^2)^2} \leq \frac{1}{\min\{1, \alpha\}} \|\mathcal{U}^0(T) - \mathcal{U}_T\|_{V^1(\mathbb{T}^2)^2} \leq \frac{3\varepsilon}{\min\{1, \alpha\}}.$$

Theorem 1.4 is proved. \blacksquare

ACKNOWLEDGMENTS

This work was partially done during the visit of the first author at the Vietnam Institute for Advanced Study in Mathematics (VIASM). The first author is thankful to the VIASM for the financial support and for the very kind hospitality of the institute and of all the staff.

REFERENCES

- [1] A. Agrachev and A. Sarychev, Navier-Stokes equations: controllability by means of low modes forcing, *Journal of Mathematical Fluid Mechanics*, **7**, 2005, no. 1, 108-152.
- [2] A. Agrachev and A. Sarychev, Controllability of 2D Euler and Navier-Stokes equations by degenerate forcing, *Communications in Mathematical Physics*, **265**, 2006, no. 3, 673-697.
- [3] J.-M. Bernard, Solutions globales variationnelles et classiques des fluides de grade deux, *C. R. Acad. Sci. Paris*, **327**, 1998, Série I, 953-958.
- [4] D. Bresch, J. Lemoine, On the existence of solutions for non-stationary second grade fluids. In: Navier-Stokes equations and related non-linear problems, Palanga, 1997, pp. 1530, VSP, Utrecht, 1998.
- [5] D. Cioranescu, V. Girault, Weak and classical solutions of a family of second grade fluids, *Internat. J. Non-Linear Mech.*, **32**, 1997, 317-335.
- [6] D. Cioranescu and E. H. Ouazar, Existence and uniqueness for fluids of second grade, *Nonlinear partial differential equations and their applications. Collège de France seminar, Vol. VI (Paris, 1982/1983)*, p.178-197, Boston, MA, Pitman, 1984.
- [7] J. E. Dunn, R. L. Fosdick, Thermodynamics, stability and boundedness of fluids of complexity 2 and fluids of second grade, *Arch. Ration. Mech. Anal.*, **56**, 1974, 191-252.
- [8] C. Foias, D. Holm, E. S. Titi, The Navier-Stokes-alpha model of fluid turbulence, Special Issue in Honor of V. E. Zakharov on the Occasion of His 60th Birthday, *Phys. D*, **152**, 2001, 505-519.
- [9] C. Foias, D. Holm, E.S. Titi, The three-dimensional viscous Camassa-Holm equations and their relation to the Navier-Stokes equations and turbulence theory, *J. Dynam. Differential Equations*, **14**, 2002, 1-35.
- [10] A. V. Fursikov, and O. Yu. Imanuvilov, On exact boundary zero-controllability of two-dimensional Navier-Stokes equations *Acta Applicandae Mathematicae*, **37**, 1994, no. 1-2, 67-76.
- [11] A. V. Fursikov, and O. Yu. Imanuvilov, Local exact controllability of the Navier-Stokes equations, *C. R. Acad. Sci. Paris Sér. I Math.*, **323**, 1996, no. 3, 275-280.
- [12] A. V. Fursikov, and O. Yu. Imanuvilov, Controllability of evolution equations, *Lecture Notes Series*, **34**, Seoul National University, Research Institute of Mathematics, Global Analysis Research Center, Seoul, 1996.
- [13] G. P. Galdi, K. R. Rajagopal, Slow motion of a body in a fluid of second grade, *International Journal of Engineering Science*, **35**, 1997, 33-54.
- [14] G. P. Galdi, A. Sequeira, Further existence results for classical solutions of the equations of second grade fluids, *Arch. Rat. Mech. Anal.*, **128**, 1994, 297-312.
- [15] G. P. Galdi, M. Grobbelaarvandalsen, N. Sauer, Existence and uniqueness of classical solutions of the equations of motion for 2nd-grade fluids, *Arch. Rat. Mech. Anal.*, **124**, 1993, 221-237.
- [16] G. P. Galdi, M. Grobbelaarvandalsen, N. Sauer, Existence and uniqueness of solutions of the equations of motion for a fluid of second grade with non-homogeneous boundary conditions, *Int. J. Non-Linear Mech.*, **30**, 1995, 701-709.
- [17] V. Girault, M. Saadouni, On a time-dependent grade-two fluid model in two dimensions, *Computers and Mathematics with Applications*, **53**, 2007, 347-360.
- [18] V. Girault, L.R. Scott, Analysis of a two-dimensional grade-two fluid model with a tangential boundary condition, *J. Math. Pures Appl.*, **78**, 1999, 981-1011.
- [19] V. Jurdjevic, Geometric Control Theory, Cambridge University Press, Cambridge, 1997.
- [20] C. Le Roux, Existence and uniqueness of the flow of second-grade fluids with slip boundary conditions, *Arch. Rational Mech. Anal.*, **148**, 1999, 309-356.
- [21] I. Moise, R. Rosa, X. Wang, Attractors for non-compact semigroups via energy equations, *Nonlinearity*, **11**, 1998, no. 5, p.1369-1393.

- [22] H. Nersisyan, Controllability of 3D incompressible Euler equations by a finite-dimensional external force, *ESAIM Control Optim. Calc. Var.*, **16**, 2010, no. 3, 677-694.
- [23] M. Paicu, G. Raugel, Dynamics of second grade fluids: the Lagrangian approach, *Recent Trends in Dynamical Systems, Springer Proceedings in Mathematics & Statistics*, Volume 35, 2013, 517-553.
- [24] M. Paicu, G. Raugel, A. Rekaló, Regularity of the global attractor and finite-dimensional behavior for the second grade fluid equations, *J. Differential Equations*, **252**, 2012, no. 6, 3695-3751.
- [25] R. S. Rivlin, J. L. Ericksen, Stress-deformation relations for isotropic materials, *J. Ration. Mech. Anal.*, **4** (4), 1955, 323-425.
- [26] A. Shirikyan, Approximate controllability of three-dimensional Navier-Stokes equations, *Communications in Mathematical Physics*, **266**, 2006, no. 1, 123-151.
- [27] A. Shirikyan, Contrôlabilité exacte en projections pour les équations de Navier-Stokes tridimensionnelles [Exact controllability in projections for three-dimensional Navier-Stokes equations], *Ann. Inst. H. Poincaré Anal. Non Linéaire*, **24**, 2007, no. 4, 521-537.

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