様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　５ 年　６ 月 １２ 日現在

機関番号：３８００５
研究種目：若手研究
研究期間：2020～2022
課題番号：２０Ｋ１４６５６

研究課題名（和文）Purely Elastic Flow-induced Vibrations of Microcylinders : Viscoelastic Fluid-Structure Interaction in Microfluidics

研究課題名（英文）Purely Elastic Flow-induced Vibrations of Microcylinders : Viscoelastic Fluid-Structure Interaction in Microfluidics

研究代表者
Ｈｏｐｋｉｎｓ　Ｃａｍｅｒｏｎ（Hopkins, Cameron）

沖縄科学技術大学院大学・マイクロ・バイオ・ナノ流体ユニット・ポストドクトラルスカラー

研究者番号：５０８６５９５４

交付決定額（研究期間全体）：（直接経費）　　2,700,000円

研究成果の概要（和文）：粘弾性流体は、粘性流体と弾性固体の性質を持ちます。生物システムおよび工業システムの多くでは、このような流体が細長い形状の障害物と相互作用し、その相互作用はマイクロ流路内の円柱を通過する流れとしてモデル化することができる。長さスケールが十分に小さい場合、流体の持つ弾性が流れを支配するため、弾性に起因する流体の不安定流れを引き起こす。本研究では、細長い障害物とその周囲を流れる粘弾性流体との間の相互作用を特徴づけることを目的とした。その結果、いくつかの条件で弾性起因の新しい不安定性流れを発見し、その特性を明らかにした。この研究は、粘弾性流れに関する基礎研究の発展に向けた基盤を確立するものである

研究成果の学術的意義や社会的意義
The research is of interest to the microfluidics, fluid mechanics, rheology, and broader engineering and physics communities and has resulted in 9 papers published in international peer-reviewed journals. The research findings improve our understanding of viscoelastic flow instabilities.

研究成果の概要（英文）：Viscoelastic fluids have intermediate properties between viscous fluids and elastic solids. These fluids interact with slender objects in many biological and industrial systems, and the interactions can be modelled as flow past a cylinder in a microchannel. At small enough length scales fluid elasticity dominates the flow, leading to purely elastic flow instabilities. The aim of this project was to characterize the interaction between viscoelastic fluids and slender objects. As a result, novel elastic flow instabilities were discovered and characterized in several systems. This work establishes a foundation for future fundamental research in viscoelastic flows.

研究分野：Viscoelastic Fluid Dynamics

キーワード：viscoelasticity　microfluidics　flow instability　cylinder　rheology　wormlike micelles　polymers　non-Newtonian fluids

１．研究開始当初の背景

Viscoelastic fluids have intermediate properties between viscous fluids and elastic solids. These fluids interact with slender objects in many biological and industrial systems, and the interactions can be modelled as flow past a cylinder in a microchannel. At small enough length scales fluid elasticity dominates the flow, leading to purely elastic flow instabilities. The aim of this project was to characterize the interaction between viscoelastic fluids and slender objects. As a result, novel elastic flow instabilities were discovered and characterized in several systems. This work establishes a foundation for future fundamental research in viscoelastic flows.

２．研究の目的

The purpose of this project:

1. To study the interaction between slender microscopic objects such as cilia or fibers and viscoelastic fluids under flow conditions where the fluid elasticity dominates the flow behaviour.
2. Broaden our understanding of purely elastic flow instabilities in microfluidic channels containing microcylinders

３．研究の方法

The research method for this project involved:

1. Fabrication of microfluidic channels containing a microcylinder using selective laser-induced etching of glass.
2. Preparation of viscoelastic fluids containing wormlike micelles from a salt-surfactant solution, and the characterization of their rheological properties (viscosity, relaxation time, viscoelastic moduli, etc.)
3. Flow of the viscoelastic fluids through the microfluidic channels over a range of imposed flow rates and the measurement of their flow behaviour using high-speed particle image velocimetry (PIV)
4. The analysis and characterization of the results over a wide range of imposed flow rates and microchannel geometry.

４．研究成果

This project has resulted in 9 papers published in international peer-reviewed journals and 3 contributed talks at international conferences (which were limited by the impacts of the COVID-19 pandemic).

The research is of interest to the microfluidics, fluid mechanics, rheology, and broader engineering and physics communities. In particular, the discovered viscoelastic flow instabilities around a cylinder may impact non-Newtonian flows in various industrial and biological systems and provide a foundation for future work on theoretical and computational fluid dynamics.

This project initially aimed to investigate the interaction between a viscoelastic fluid and a slender, flexible cylinder, which served as a model for biological cilia. The research built upon prior studies on flow past a single rigid cylinder [1,2] and two flexible cylinders [3]. However, the project took a new direction when two novel viscoelastic flow instabilities were discovered. In order to gain a deeper understanding of the underlying fluid dynamics before introducing the complexity of a flexible cylinder, the flow instabilities were examined in the context of rigid cylinders. All experiments described in this study were conducted using a viscoelastic wormlike micellar solution in microchannels with length-scales small enough that inertia in the flows was negligible, hence the flow behavior was entirely governed by fluid elasticity

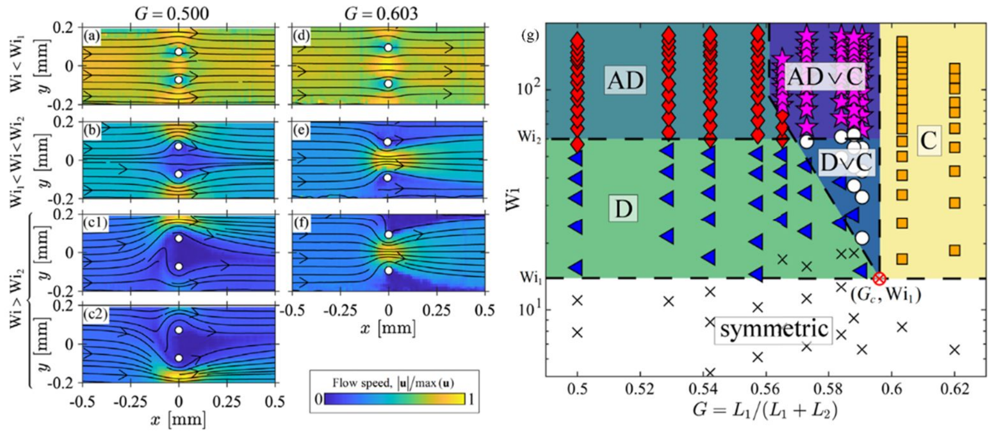

Figure 1 – Evolution of velocity fields with Wi for viscoelastic flow past two side-by-side cylinders with varying gap parameter. $G = 0.500$ (a)-(c) and $G = 0.603$ (d) - (f). Panels (c1) and (c2) indicate the two possible states for G = 0.500 and $Wi > Wi_2$. (g) Flow stability diagram in Wi-G state space. The dashed lines and colored shades delineate between flow states. From Ref. [4].

The first discovery pertains to the flow past two side-by-side cylinders in a microchannel [4], as illustrated in Figure 1. The observed flow behaviors exhibit stark differences depending on the dimensionless gap $G = L_1/(L_1 + L_2)$ between the cylinders, where L_1 represents the intercylinder distance and L_2 represents the distance between the cylinders and side walls. With an increasing Weissenberg number $Wi = \lambda U/R$, where λ is the fluid relaxation time, U is the average flow velocity, and R is the cylinder radius, a series of flow bifurcations occur depending on G. The Weissenberg number quantifies the relative strength of elasticity to viscosity in the flow. When G is sufficiently small, for instance, $G = 0.5$ as depicted in Figure 1 (a-c), the flow remains steady and symmetric (Figure 1 (a)) for Wi values below a critical Weissenberg number Wi_1. Within the range of $Wi_1 < Wi < Wi_2$, the flow bifurcates and passes symmetrically around the two cylinders, a state referred to as the Diverging (D) flow state. As Wi exceeds the second critical Weissenberg number Wi_2, two distinct states emerge: the Asymmetric Diverging (AD) flow states (Figure 1 (c1) and (c2)). In these states, the fluid randomly chooses either the top or bottom gap as a preferential pathway for flow. Both possibilities remain stable over time, leading to a bi-stable flow state.

If the dimensionless gap G is sufficiently large, for example $G = 0.603$ as depicted in Figure 1 (d-f), different flow behaviour is observed. When $Wi > Wi_1$, the flow predominantly passes through the intercylinder gap while avoiding the space between the cylinders and side walls. This behaviour is referred to as the Converging (C) flow state. Increasing Wi further intensifies the flow between the cylinders without causing any additional qualitative changes in the flow behaviour over the range of Wi investigated. The transitions from the steady and symmetric state to the D or C state, as well as the transition from D to AD state, are characterized as imperfect forward (supercritical) pitchfork bifurcations [4].

Within a range of intermediate G values, for $Wi_1 < Wi < Wi_2$, either the Diverging or

Converging flow state can be observed in a given experiment within the same channel, forming the D or C ($D \vee C$) triangular region in the $Wi - G$ flow-phase diagram shown in Figure 1 (g). Both flow states are stable, indicating the presence of a region of bi-stability. For $Wi > Wi_2$, three possible states can be observed: the two Asymmetric Diverging flow states, or the Converging flow state, as indicated by the region labelled $AD \vee C$ in Figure 1 (g). Therefore, this region demonstrates tri-stability. This represents the first reported observation of multistability in viscoelastic flows and provides fundamental insights into how viscoelastic fluids select preferred paths when flowing through ordered and disordered porous arrays [4,5].

The second novel instability discovered in this project involves the observation of upstream wall-attached vortices in the flow past a single rigid cylinder within a microchannel [6,7]. The time-steady and time-dependent behaviour of this instability was extensively examined for a cylinder-channel geometry with a blockage ratio $B_R = 2R/W = 0.5$, where W is the width of the channel [6]. Consequently, a more comprehensive analysis of the flow past a cylinder was conducted across a range of B_R and Wi, with the findings presented in Ref. [7] and summarized in this section.

Figure 2 (a) presents a $Wi - B_R$ flow state diagram, accompanied by velocity fields and turbulence intensity fields that illustrate the diverse flow behaviour observed in the flow past a cylinder system. Different symbols in the diagram correspond to the various steady and time-dependent flow states depicted in Figure 2 (b-i). The dashed lines denoted by the critical Weissenberg numbers Wi_{c1} and Wi_{c2} indicate the stability boundaries between these flow states.

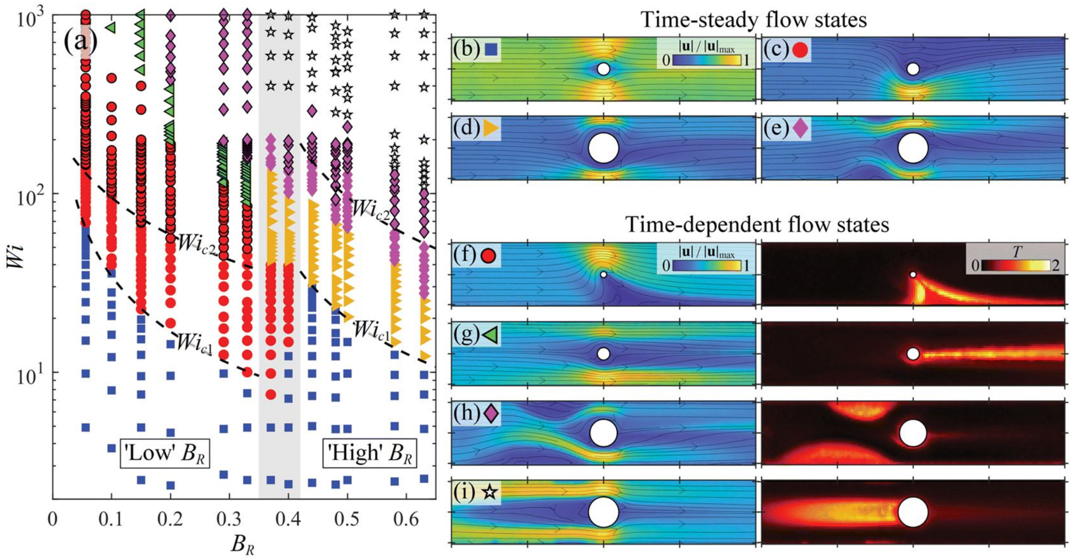

Figure 2 – (a) Flow state diagram in Wi–B_R state space. Colored symbols represent different steady and time-dependent flow states depicted to the right, as indicated by corresponding symbols: (b) low-Wi ‘symmetric’ state (B_R = 0.2, Wi = 9.5); (c) ‘laterally asymmetric’ state (B_R = 0.2, Wi = 43); (d) ‘upstream bending streamlines’ (B_R = 0.48, Wi = 53); (e) ‘upstream wall vortices’ (B_R = 0.48, Wi = 82); (f) ‘time-dependent laterally asymmetric’ state (B_R = 0.1, Wi = 257); (g) ‘asymmetric jetting’ (B_R = 0.2, Wi = 384); (h) ‘time-dependent upstream wall vortices’ (B_R = 0.44, Wi = 160); (i) ‘upstream cylinder vortex’ (B_R = 0.48, Wi = 481). From Ref. [6]

For ‘low’ blockage ratios, $B_R \leq 0.33$, when $Wi < Wi_{c1}$, the flow remains steady and symmetric, as shown in Figure 2 (b). As Wi exceeds Wi_{c1}, a symmetry-breaking bifurcation occurs, resulting in laterally asymmetric flow where one side of the cylinder becomes preferential for flow, as depicted in Figure 2 (c). With further increase in Wi beyond Wi_{c2}, the flow state transitions into a time-dependent laterally asymmetric state, as presented in Figure 2 (f). In this state, periodic pulsations occur in the flow, causing the region of slow-moving fluid on the lower side of the cylinder to expand and contract. The turbulence intensity field in the right panel of Figure 2 (f) shows the highest intensity near the boundary between the fast-moving and slow-moving fluid, illustrating that the time-dependent changes in the flow field are concentrated in that region. As Wi continues to increase, a previously unreported flow state labelled 'asymmetric jetting' emerges, as shown in Figure 2 (g). This state is characterized by asymmetric flow past the cylinder combined with time-dependent pulsations in the downstream wake of the cylinder. Finally, further increasing Wi leads to the formation of time-dependent wall vortices upstream of the cylinder, which vary in position and size over time, as depicted in Figure 2 (h).

For 'high' blockage ratio $B_R \geq 0.44$, the laterally asymmetric flow state does not occur. Instead, as Wi increases beyond Wi_{c1}, there is a transition from steady and symmetric flow to a state characterized by bending streamlines upstream of the cylinder, as shown in Figure 2 (d). Further increase in Wi, but prior to the onset of time dependence at $Wi = Wi_{c2}$, leads to the formation of time-steady wall-attached vortices upstream of the cylinder, as illustrated in Figure 2 (e). These wall vortices subsequently become time-dependent as Wi exceeds Wi_{c2}. Additionally, with further increase in Wi, another vortex forms at the upstream pole of the cylinder, as depicted in Figure 2 (i). In this state, the cylinder-attached vortex competes with the wall-attached vortices for space and time within the channel, resulting in highly chaotic and time-dependent flow.

For 'intermediate' values of B_R, the evolution of flow states with increasing Wi is less well-defined compared to the low- or high-B_R regimes. This lack of clear definition is likely due to the competing influences of instabilities arising from the stagnation points at the upstream and downstream poles of the cylinder.

The findings of this study demonstrate that viscoelastic flow in a simple geometry, consisting of a single obstacle within a channel, exhibits a wide range of time-steady and time-dependent flow behaviors. These results provide a foundation for future investigations on viscoelastic flow past obstacles in microchannels and can be valuable in the design of microfluidic systems, such as biomedical lab-on-a-chip devices, that involves the use of viscoelastic fluids.

References:

[1] S. Varchanis, C. C. Hopkins, A. Q. Shen, J. Tsamopoulos, and S. J. Haward, Asymmetric flows of complex fluids past confined cylinders: A comprehensive numerical study with experimental validation, Phys. Fluids, 32, 053103 (2020),
[2] S. J. Haward, C. C. Hopkins, S. Varchanis, and A. Q. Shen, Bifurcations in flows of complex fluids around microfluidic cylinders, Lab Chip, 21, 4041 (2021)
[3] C. C. Hopkins, S. J. Haward, and A. Q. Shen, Purely elastic fluid-structure interactions in microfluidics: Implications for mucociliary flows, Small, 16, 1903872 (2020)
[4] C. C. Hopkins, S. J. Haward, and A. Q. Shen, Tristability in viscoelastic flow past side-by-side microcylinders, Phys. Rev. Lett. 126, 054501 (2021)
[5] S. J. Haward, C. C. Hopkins, and A. Q. Shen, Stagnation points control chaotic fluctuations in viscoelastic porous media flow, Proc. Natl. Acad. Sci. 118, e2111651118 (2021)
[6] C. C. Hopkins, S. J. Haward and A. Q. Shen, Upstream wall vortices in viscoelastic flow past a cylinder, Soft Matter, 18, 4868 (2022)
[7] C. C. Hopkins, S. J. Haward and A. Q. Shen, Effect of blockage ratio on flow of a viscoelastic wormlike micellar solution past a cylinder in a microchannel, Soft Matter, 18, 8856 (2022)

５．主な発表論文等

〔雑誌論文〕　計9件（うち査読付論文　9件／うち国際共著　3件／うちオープンアクセス　9件）

１．著者名 Varchanis Stylianos、Haward Simon J.、Hopkins Cameron C.、Tsamopoulos John、Shen Amy Q.	４．巻 307
２．論文標題 Evaluation of constitutive models for shear-banding wormlike micellar solutions in simple and complex flows	５．発行年 2022年
３．雑誌名 Journal of Non-Newtonian Fluid Mechanics	６．最初と最後の頁 104855～104855
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jnnfm.2022.104855	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Hopkins Cameron C.、Shen Amy Q.、Haward Simon J.	４．巻 18
２．論文標題 Effect of blockage ratio on flow of a viscoelastic wormlike micellar solution past a cylinder in a microchannel	５．発行年 2022年
３．雑誌名 Soft Matter	６．最初と最後の頁 8856～8866
掲載論文のDOI（デジタルオブジェクト識別子） 10.1039/D2SM01162J	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Hopkins Cameron C.、Haward Simon J.、Shen Amy Q.	４．巻 18
２．論文標題 Upstream wall vortices in viscoelastic flow past a cylinder	５．発行年 2022年
３．雑誌名 Soft Matter	６．最初と最後の頁 4868～4880
掲載論文のDOI（デジタルオブジェクト識別子） 10.1039/D2SM00418F	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

１．著者名 Haward Simon J.、Hopkins Cameron C.、Varchanis Stylianos、Shen Amy Q.	４．巻 21
２．論文標題 Bifurcations in flows of complex fluids around microfluidic cylinders	５．発行年 2021年
３．雑誌名 Lab on a Chip	６．最初と最後の頁 4041～4059
掲載論文のDOI（デジタルオブジェクト識別子） 10.1039/D1LC00128K	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

1．著者名 Haward Simon J.、Hopkins Cameron C.、Shen Amy Q.	4．巻 118
2．論文標題 Stagnation points control chaotic fluctuations in viscoelastic porous media flow	5．発行年 2021年
3．雑誌名 Proceedings of the National Academy of Sciences	6．最初と最後の頁 e2111651118
掲載論文のDOI（デジタルオブジェクト識別子） 10.1073/pnas.2111651118	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

1．著者名 Haward Simon J.、Hopkins Cameron C.、Shen Amy Q.	4．巻 278
2．論文標題 Asymmetric flow of polymer solutions around microfluidic cylinders: Interaction between shear-thinning and viscoelasticity	5．発行年 2020年
3．雑誌名 Journal of Non-Newtonian Fluid Mechanics	6．最初と最後の頁 104250～104250
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.jnnfm.2020.104250	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

1．著者名 Hopkins Cameron C.、Haward Simon J.、Shen Amy Q.	4．巻 126
2．論文標題 Tristability in Viscoelastic Flow Past Side-by-Side Microcylinders	5．発行年 2021年
3．雑誌名 Physical Review Letters	6．最初と最後の頁 54501
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.126.054501	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

1．著者名 Varchanis Stylianos、Hopkins Cameron C.、Shen Amy Q.、Tsamopoulos John、Haward Simon J.	4．巻 32
2．論文標題 Asymmetric flows of complex fluids past confined cylinders: A comprehensive numerical study with experimental validation	5．発行年 2020年
3．雑誌名 Physics of Fluids	6．最初と最後の頁 053103～053103
掲載論文のDOI（デジタルオブジェクト識別子） 10.1063/5.0008783	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

1．著者名 Varchanis Stylianos、Haward Simon J.、Hopkins Cameron C.、Syrakos Alexandros、Shen Amy Q.、Dimakopoulos Yannis、Tsamopoulos John	4．巻 117
2．論文標題 Transition between solid and liquid state of yield-stress fluids under purely extensional deformations	5．発行年 2020年
3．雑誌名 Proceedings of the National Academy of Sciences	6．最初と最後の頁 12611～12617
掲載論文のDOI（デジタルオブジェクト識別子） 10.1073/pnas.1922242117	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

〔学会発表〕　計4件（うち招待講演　0件／うち国際学会　4件）

1．発表者名 Hopkins Cameron C., Haward Simon J., Shen Amy Q.
2．発表標題 Flow-induced vibrations due to the flow of a viscoelastic fluid between two cantilevered microcylinders
3．学会等名 International Congress of Theoretical and Applied Mechanics（国際学会）
4．発表年 2021年

1．発表者名 Hopkins Cameron C., Haward Simon J., Shen Amy Q.,
2．発表標題 Tristability in viscoelastic flow past side-by-side microcylinders
3．学会等名 The Annual European Rheology Conference in Cyberspace（国際学会）
4．発表年 2021年

1．発表者名 Varchanis Stylianos, Hopkins Cameron C., Shen Amy Q., Tsamopoulos J., Haward Simon J.
2．発表標題 Asymmetric flows of complex fluids past a cylinder in a microchannel
3．学会等名 The Annual European Rheology Conference in Cyberspace（国際学会）
4．発表年 2021年

１．発表者名 Hopkins Cameron C.、Haward Simon J.、Shen Amy Q.
２．発表標題 Tristability in Viscoelastic Flow Past Side-by-Side Microcylinders
３．学会等名 Annual European Rheology Conference 2021（国際学会）
４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関