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Applicant(s)

Assignee(s): The Board of Trustees of the Leland Stanford Junior University

Licensee(s):

Associate:

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Prosecution History

0 1 2 3 4 5 6 7 8

10/2/2024 **FITNS**

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Active **FORM-ASSN**

US Provisional Patent Application

for

Tethered Swimming Rheometer

by

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GOVERNMENT SPONSORSHIP

This invention was made with Government support under contract 2210532 awarded by the National Science Foundation. The Government has certain rights in the invention.

SUMMARY

Rheological properties of various fluids (biological or engineered fluids) play a fundamental role in everything from medicine to consumer applications. Rheometry (i.e. the measurement of the mechanical properties of a fluid) is presently accomplished via a variety of expensive machines (typically referred to as “rheometers”) that require advanced training to operate and are designed to replicate the non-equilibrium environment in which the fluid of interest resides or might reside. Usually, significant volumes of the fluid must be extracted and taken to the machine for measurement. Finally, it is well known that for

complex fluids, the mechanical properties depend on the scale of the fluid volume present in the particular flow, whereas present rheometers typically can only assess the mechanical properties at fixed (large) scales. Thus, in many applications, where rheological measurements are extremely important to assess the operation of the fluid, they are extremely difficult or not possible.

The device as we describe below is a tethered swimming “robot” that can be placed in a fluid remotely, e.g. on the boundaries. It then creates a swimming propulsive force which is measured by a load cell attached to the tether. It reports this force along with other measures of the motion to a remote data collector in real time from which the local fluid properties can be determined. The scale and location of the robot determines the scale and location of the mechanical properties measured. The size of the swimming robot can be varied from a few microns to meter size, and the scale of the robot also determines the scale of the volume of fluid necessary for measurement – thus in principle very small volumes of fluid in their native environment can be assessed. Once calibrated, the robot is easy to use, highly portable and the post processing of the data can be done using something as simple as an application on a cell phone. We have already demonstrated that this new measurement technique is highly sensitive to fluid properties by making measurements of an existing fluid in parameter regimes that have not been accomplished heretofore.

A tethered swimmer – i.e. like a fish caught on a line -- produces propulsion in a complex fluid (with complex described more precisely below). In this context, the three material properties in shear that describe the state of stress under nonlinear conditions (i.e. far from equilibrium) in a sheared fluid are the viscosity, primary normal stress coefficient, ψ_1, and second normal stress coefficient ψ_2. These material properties may be functions of time (or frequency) if the applied shear is not steady. In near equilibrium or under linear deformation, the viscosity is the primary material property. A “simple” or Newtonian fluid for the purposes of this document will be one in which the viscosity is the only measurable and important fluid property under all conditions and is a constant – i.e. independent of the magnitude of shear rate and time. Examples include water, air, and most small molecule liquids. All other fluids will be referred to as complex, and examples include many biological fluids, e.g. mucous and blood, all liquid plastics, geological fluids (e.g. magma), cements and concretes, and so forth.

Thus, references [1,2] describe a class of swimming motions that can be programmed into an untethered mechanical swimmer where the motions are sensitive to the primary normal stress coefficient in a liquid – essentially, there is no propulsion in a simple fluid but there is in a complex fluid. The motion described in [1,2] is for steady propulsion. References [1,2] are hereby incorporated by reference in their entirety. See also PCT application PCT/US2022/039724 entitled " A Multi-Mode Mechanical Swimmer That Acts as a Rheometer", and hereby incorporated by reference in its entirety.

Here we describes a new approach to measurement of physical properties of a given fluid – utilizing measurements of a tethered microscopic swimmer and its behavior in a fluid of interest. We consider design of tethered micro-swimmers capable of making these measurements in complex fluids; at length scales ranging from microns to meters. We further present four constructed tethered micro-swimmers as representative of a broad class of such swimmers and use these tethered swimmers to make measurements in a fluid of interest.

We have demonstrated in previous work[1,2] that steady, counter rotation of connected objects of different sizes/shapes (referred to as a "head" and a "tail") in the appropriate publication[1,2]) creates propulsion in a complex fluid and not in a simple fluid. Thus a freely suspended object "swims" if the onboard motor creates such a counter rotation. We have demonstrated, Fig. 1, that if the same class of swimmers is tethered there is a resulting force on the tether in complex fluids which may be compressional or extensional. This has been demonstrated by a) large scale computations as well as b) the creation of mechanical prototypes as described below. Moreover, we have demonstrated that the *propulsive force* increases with the increase in normal stress coefficients and hence *elasticity* of the fluid. In fact, we have demonstrated that in the so-called weak flow regime, the force is proportional to the sum $\psi_1 + 2\psi_2$. Thus, this tethered swimming force can be used as a rheometric measurement of the normal stress coefficients for a wide class of fluids.

This conception of the rheometer is very different than that described for the freely suspended swimmer in [1,2]. The primary measurable here is the *propulsion force*, not the *swim velocity* (as in [1, 2]). Because complex fluids are nonlinear in their force-velocity relationship, the properties of the propulsion force are not easily understood from the velocity, nor is there a simple correlation between them. Moreover, the properties of the force (i.e. dependence on fluid properties, dependence on the geometry of the swimmer, and so forth) are not easily gleaned from the swim velocity. Thus the interpretation of the force measurement as a rheological measurement exists nowhere in the literature and was developed as part of this work. Moreover, optimization of the tethered swim rheometer was accomplished completely independently of any optimization of the swim velocity for an untethered swimmer.

The conception, creation and operation of the tethered swimming rheometer has already been completed and is described briefly below. A pair of cylindrically symmetric bodies are connected via a freely rotating joint (shown as magnets in Fig. 1) and immersed in a complex fluid. One of the bodies is "smaller" and is the tail, while the other is "larger" and is the head. The terms "smaller" and "larger" in this context refer to the relative size of the scale l_c that define the relationship between the torque, L, and the angular velocity, Ω, of the rotation of the bodies alone in an unbound Newtonian fluid of viscosity η, viz. $L = 8\pi\eta l_c^3\Omega$.

Either the tail or head is tethered to a load cell via a thin rigid tether that can transmit force to the load cell either in compression or extension. In particular, the tether should not bend or absorb load under compression, and it should transmit force in both compression and extension. The tether is free to rotate within the coupling to the load cell. A motor in the "head" is remotely engaged and enforces a relative rotation between the head and the tail. As there is no net torque imposed on the swimmer, both head and tail will counter-rotate and the speed of rotation will be larger for the tail. Upon onset of the counter rotation, a thrust will be generated in the direction of the head through its interaction with the complex fluid in which it is immersed. This propulsion force is recorded via the load cell as a function of time until a steady force is achieved. The observables then are the a) Propulsive force as a function of time and b) the head rotation rate as a function of time. Note the tail rotation rate may also be measured as a check on the relative rotation rate imposed by the motor. The head rotation rate is measured either via visualization or through a gyroscope in the head. The imposed counter rotation can be any time dependent dynamic sequence, however for steady measurements of the fluid properties, a "step up" to a steady counter rotation followed by a step down to no counter rotation is preferred for simplicity. Note that the swimmer is most conveniently oriented along gravity so the buoyant weight of the swimmer can be zeroed in the load cell before the counter rotation commences, thus assuring that the measurement is of the propulsive force alone. Data is taken as propulsive force as a function of time as shown in Fig. 2.

The force data can either be extensive or compressive. Note that drift in the load cell zero may simply be subtracted and slight misalignment of the counter rotating bodies results in precession (oscillations of the signal) but these may be averaged (cf. Fig. 2). Force is recorded as a function of tail rotation rate (cf. Fig. 3). Such measurements are made for a range of rotation rates extending from "small" rotation rate to "large" rate with these measures defined in terms of the Deborah Number, De=$\Omega_T\lambda$, where Ω_T is the rotation rate of the tail and λ is a fluid relaxation time determined from the relaxation of the propulsive force as measured from the step down part of the cycle (see below). Therefore De < 1 is small rotation rate and De > 1 is large rotation rate. In the "small rotation rate limit" it can be shown that the swim force is related to the primary normal stress coefficients through the equation:

$$F = a\,\Omega_T^2$$

$$a = (\psi_1 + 2\psi_2)l_c^2 f(geom.)$$

where f(geom.) is a function of the geometry of the head and tail that can be determined exactly through computation. Thus measurements of the force can be fit to the equation above and the determination of "a" allows direct measure of the sum of the normal stress coefficients. An example of those measurements is shown in Fig. 3

The measurements are fit to a polynomial the form of which is dictated by the symmetry of the physical situation and "a" is extracted. Note that each time a new head/tail pair is used the measurements correspond to a "new rheometer" with a new f(geom.) which again is determined via computation within negligible error.

The fluid for which Figs. 2 & 3 correspond is a classic "Boger fluid" in the literature which is a solution of high molecular weight polymers in a low molecular weight highly viscous solvent. There is a large literature on the rheology of such fluids and they are known to have a nearly constant ψ_1 and a vanishingly small value of ψ_2. Thus the data in Fig. 3 can be directly compared to rheological measurements using a state of the art benchtop rheometer. Such a comparison is made in Fig. 4. The open symbols are the measurements from the benchtop rheometer and the solid lines are those from the TSR assuming ψ_2=0. Measurements of the TSR are shown for three different head/tail configurations. The material property ψ_1 is not only consistent with the benchtop measures it is made in a range of shear rate (i.e. the average shear rate over the surface of the TSR) which is unaccessible via the benchtop rheometer. In the latter context, our measurments are made in a range of shear rate that is an order of magnitude lower shear rate than that accessible to the benchtop rheometer. For commercial applications this is a very important aspect of these measurements.

The use of this rheometer can apply to a range of measurements that far exceeds the simple measurements of the primary normal stress coefficient. Dynamic measures for complex fluids can be accurately made as well. For example, upon cessation of the motor, the propulsion force relaxes on the *relaxation time* of the fluid. This is a separate dynamic measure which is of great interest to the community. Computational simulation demonstrates that the TSR is very sensitive to the longest relaxation time even though the fluid, by its very nature has a spectrum of relaxation times. Fig. 5 shows that relaxation from one of the steady experiments in Fig. 4. Clearly plotted on a semi-log plot, there is a single relaxation time which characterizes the relaxation of the fluid and can be used to determine the appropriate De discussed above. We envisage that a host of complementary dynamic measures can be made with the TSR including a) oscillatory response of the fluid (linear viscoelasticity), b) exponential (in time) response for the fluid (extensional viscosity), c) CHIRP fluid response (alternative to linear viscoelasticity). These correspond to measures that are presently being made with benchtop rheometers. However, they can all be made with the TSR with a) enhanced sensitivity, b) remotely *in situ*, i.e. as remote sensors without fluid extraction, and c) more simply and cheaply. Moreover, in principle, the device can be tailored to the application (size, necessary fluid volume, sensitivity, etc. Note in the context of device cost, the device employed to make these measurements is < $1K in cost including all peripheral electronics.

Applications

In principle, this device has utility both as a research instrument in biological/medical and industrial manufacturing and also bringing rheological measurements to standard manufacturing processes in a very wide range of applications. The device can be an “add on” to existing rheometers as well as a remote sensor.

At present there are a host of rheometer companies including Anton Paar and TA instruments that sell devices to make rheometric measurements. Traditionally, a rheometer is a large table top device that is sensitive, relatively costly (> $10K), requires extensive training to operate and needs a large sample volume to operate. Much of these rheological measurements are made in lab conditions as a table top setup is large and cannot be done in-situ. We propose a new paradigm in measurement of rheological properties – by reversing the fundamental principal of rheological measurement. Instead of putting a small amount of fluid into a large sensitive rheometer; we put a small scale “tethered swimming robot as rheometer” inside the fluid and observe its swimming behavior to calculate the equivalent fluid properties measured otherwise by traditional means. As far as we are aware none of the traditional table top machines have many of the capabilities unique to the robot as described above. Moreover, we have already demonstrated sensitivity that exceeds the state-of-the art table top measures, at least for the steady measure of elastic fluid properties.

Advantages and Improvements over Existing Methods

The approach as described above measures the shear rheology (linear and nonlinear) of a fluid remotely, in its native state. The advantages include:

1) No harvesting of the fluid is necessary. The approach is compatible to small volumes of fluid and the rheometer can be engineered to the application involved.
2) The state of the fluid in application is the state of the measurement (temperature, pressure, etc.) without attempted reproduction of conditions.

3) In principle the measurements can be made in different locations via relocation of the sensor to examine heterogeneity of a fluid sample.

4) The scale of the measurement is the scale of the robot (which can be varied); thereby providing measurements from microns to meter scale.

5) The robots are in principle cheap relative to existing rheometers.

6) The approach proposed has the potential for multiplexing of rheological measurements (multiple head/tail combinations, multiple locations, etc.)

7) The overall approach is highly portable bringing rheology at the point of need. Collection and processing of the data can be done on a handheld device (e.g. Cell phone).

Note that there is a competing type of technology called “passive” and “active” micro-rheometry [3], where particles are introduced into a fluid and their motions are used to determine rheological properties. “Passive” micro-rheology is typically done via added Brownian particles to a fluid and examining their diffusion. Via an extension of the Stokes-Einstein relation the linear viscoelasticity of the fluid may be determined. In “active” microrheology, the particle is driven via external fields and then the motion of the particle is used to infer the fluid properties. Typically, both of these are used to determine the viscosity – either the frequency dependent or the nonlinear viscosity. The first requires spreading due to thermal motion, thus the particle samples a volume and the effective properties are an average over that volume.

Moreover, only the linear viscoelasticity can be determined. Active microrheology requires forcing externally, therefore is NOT remote and typically has been used for interfacial rheology where penetration into the fluid for the driving force is small. The TSR has advantages over both of these methods (able to measure nonlinear properties remotely without a thermal bath).

References:

[1] Binagia, J., E.S.G. Shaqfeh, “Self-propulsion of a freely suspended swimmer by a swirling tail in a vis-coelastic fluid”, Phys. Rev. Fluids, 6, 053301 (2021), DOI: 10.1103/PhysRevFluids.6.053301

[2] Kroo, L.A., J.P. Binagia, N. Eckman, M. Prakash, E.S.G. Shaqfeh, ``A freely-suspended, robotic swimmer propelled by viscoelastic normal stresses'', Journal of Fluid Mech. vol. 944, A20, (2022), doi:10.1017/jfm.2022.485

[3] Liu, W. and Wu, C., 2018. Rheological study of soft matters: A review of microrheology and microrheometers. *Macromolecular Chemistry and Physics*, *219*(3), p.1700307.

CLAIM

A rheometer for measuring one or more properties of a fluid flow, the rheometer comprising:

a swimmer unit having a head part and a tail part configured to be driven to rotate in opposite directions about a common axis of rotation;

an anchor unit;

a tether connecting the swimmer unit to the anchor unit;

wherein the anchor unit includes a force sensor configured to measure force exerted on the anchor unit by the tether;

wherein the tether is capable of transmitting both tensile force and compressive force from the swimmer unit to the anchor unit.

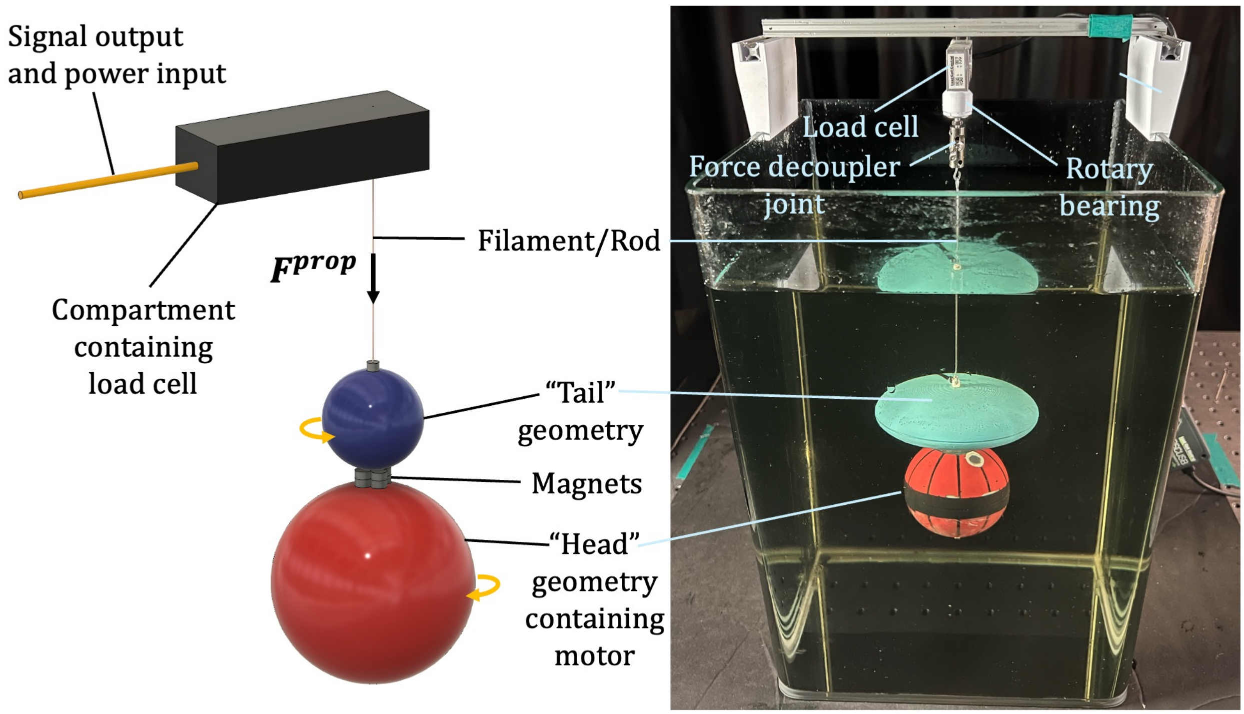

FIG. 1

Fig. 1 Schematic of the Tethered Swimming Rheometer (TSR)

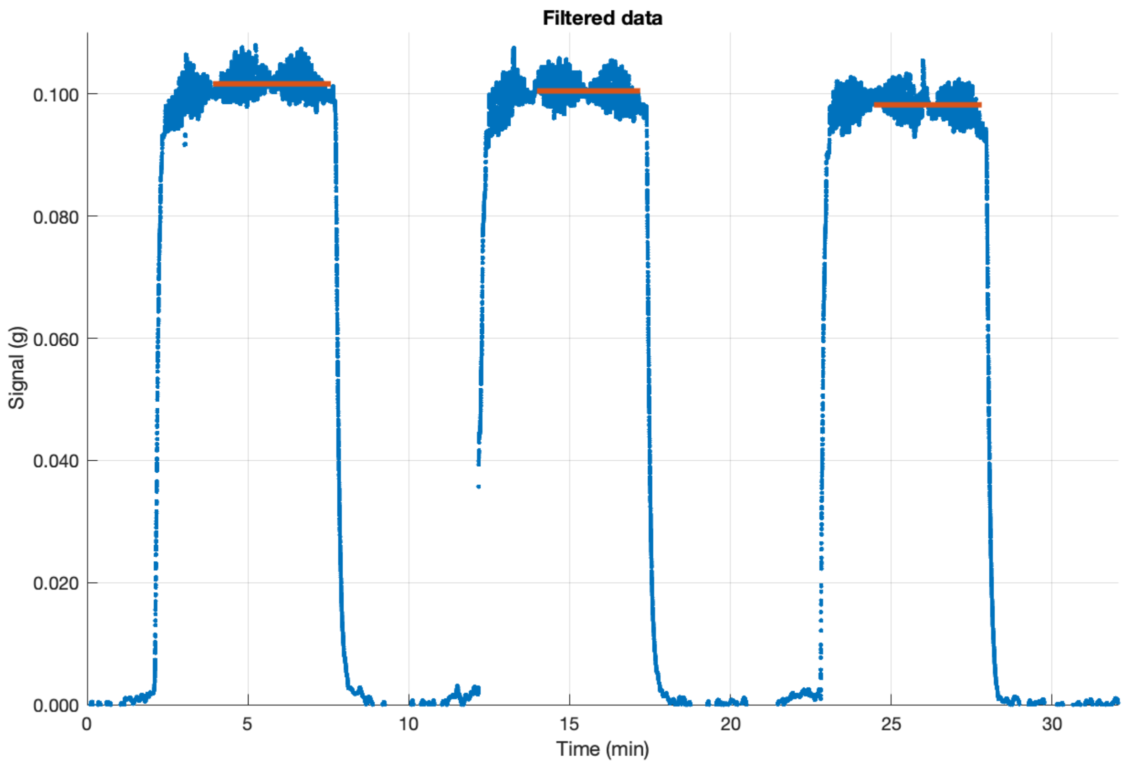

Fig. 2 Raw data of propulsive force from the tethered swimming rheometer

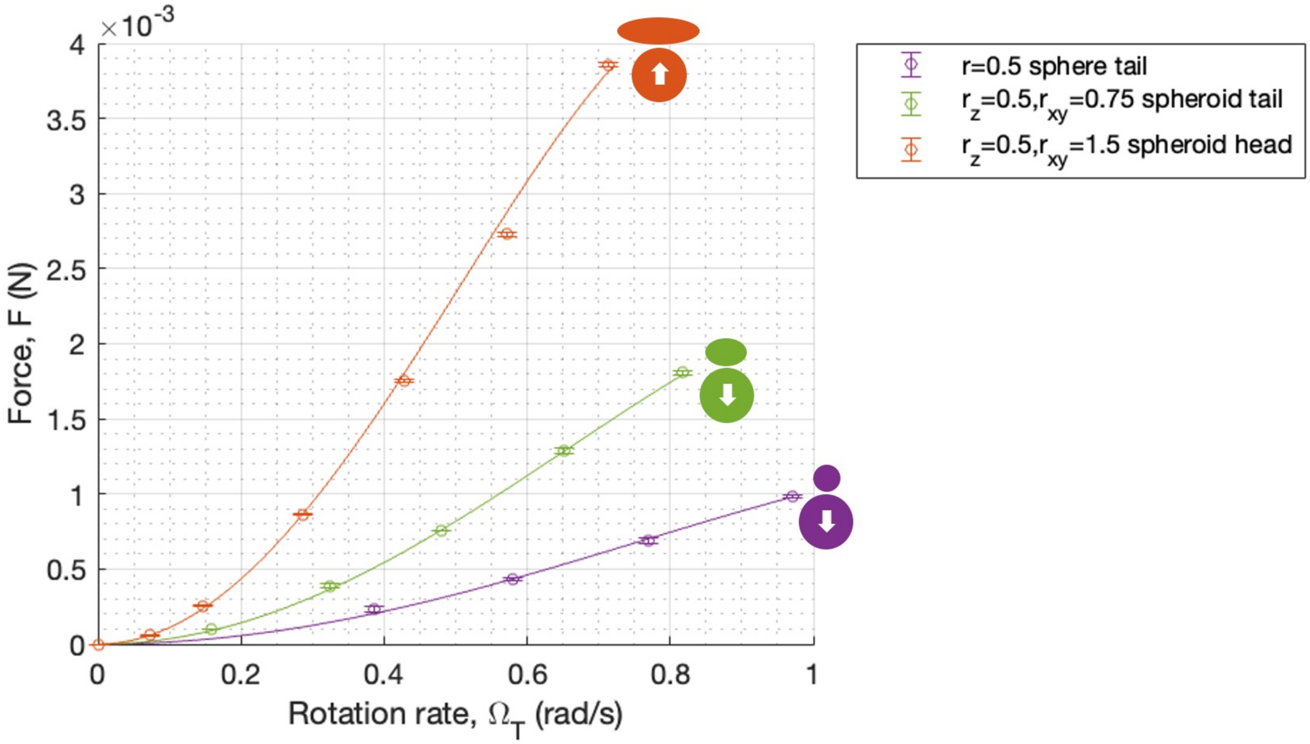

Fig. 3 Force measurements with the tethered swimming rheometer (TSR) over a range of rotation rates fit to a Taylor series (polynomial).

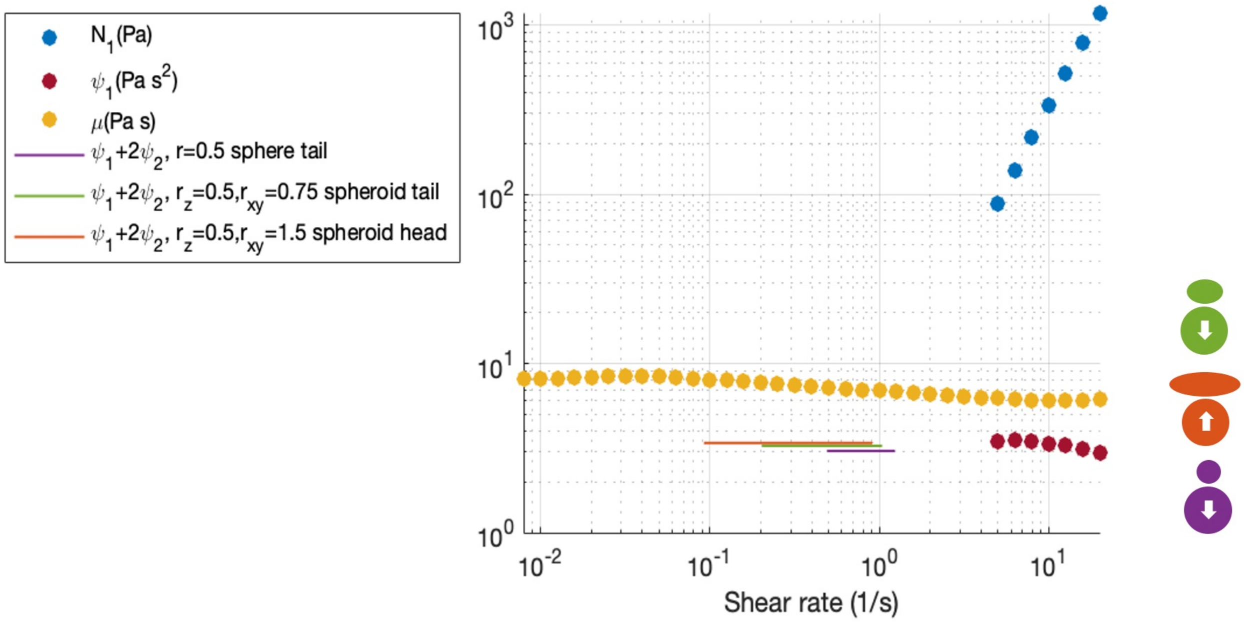

Fig. 4. Comparison to TSR measurements and that of a benchtop rheometer. Note the measurements of the benchtop rheometer are limited to the range shown because of sensitivity of the rheometer.

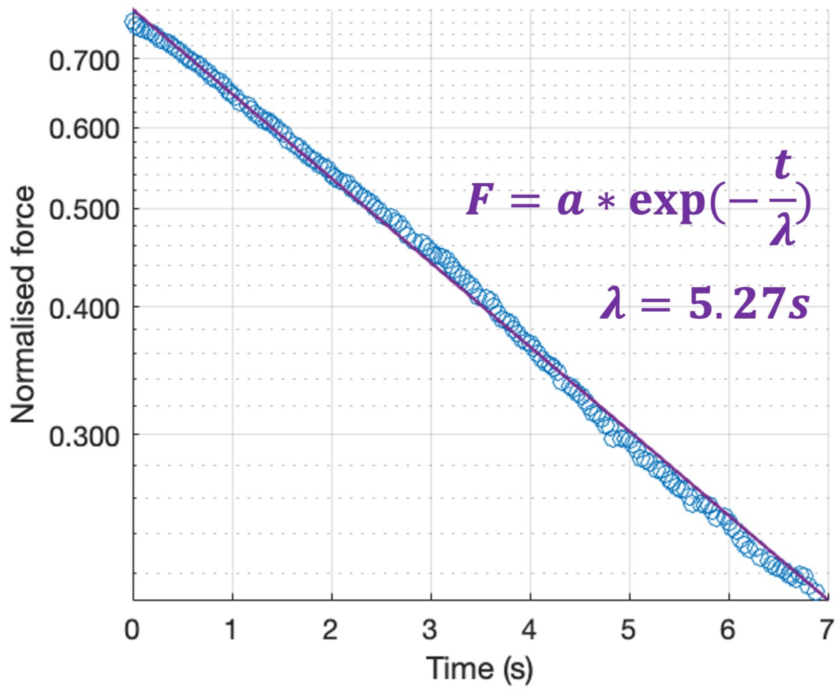

Fig. 5 Relaxation of the propulsion force with time as measured with the TSR.

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63/705,408	10/09/2024		120	S24-388/PROV		

CONFIRMATION NO. 5517

FILING RECEIPT

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Projected Publication Date: None, application is not eligible for pre-grant publication

Non-Publication Request: No

Early Publication Request: No
**** SMALL ENTITY ****
Title

Tethered Swimming Rheometer (TSR)

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