TRANSPORT VELOCITY OF DROPLETS ON RATCHET CONVEYORS IS DETERMINED BY QUANTIZED STEP PROBABILITY

Hal R. Holmes and Karl F. Böhringer[*]
University of Washington, Seattle, USA

ABSTRACT

We report the first characterization of the transport velocity for droplets driven on ratchet conveyors. Through this study, we determined that the minimum vibration amplitude to initiate droplet transport does not occur at the largest movement of the droplet edges and is thus not simply a resonance effect. We have also discovered that the transport velocity is correlated with the vibration amplitude, but ultimately determined by the probability of the droplet edges advancing by a discrete number of steps.

INTRODUCTION

The anisotropic ratchet conveyor (ARC) platform developed in our laboratory is a type of digital microfluidic (DMF) system that can transport individual liquid droplets or many droplets in parallel. Droplet transport on ARC devices is possible through the combination of two key features: 1) a microfabricated surface pattern, and 2) oscillation of the droplet footprint (contact line) [1]. The surface pattern of ARC devices consists of a periodic series of asymmetric curved features or "rungs" that are relatively hydrophilic and defined by a hydrophobic background. The asymmetry of these features creates a difference in pinning forces between the leading edge (edge in the direction of transport) and trailing edge of the droplet. Oscillation of the contact line, achieved through the application of orthogonal vibrations, cycles the droplet between wetting and de-wetting states. The combination of the contact line oscillation and the difference in pinning forces results in a net force that causes the droplet to take a step forward throughout each vibration cycle [1].

The simple functional principles and fabrication methods of ARC devices provides for an inexpensive microfluidic platform that facilitates scaled-up manufacturing. ARCs do not require electrical, thermal, or magnetic fields to drive droplet transport, which means these effects can be used to perform other processes in future applications. Further, we have previously demonstrated that programmable regimens can be enabled solely through a combination of the surface pattern geometry and applied vibration signal [2]. Overall, these properties of ARC devices demonstrate much potential to serve as an automated platform for lab-on-a-chip systems.

In this work, we characterize the transport velocity of droplets on ARC devices for the first time. We investigate how the ARC pattern and parameters of the applied vibrations affect the resulting velocity of the transported droplets. Understanding the capabilities and fundamental mechanics of the ARC system is key to orchestrating the application of ARC devices in future lab-on-a-chip systems.

MATERIALS AND METHODS

ARCs were fabricated through vapor deposition of per-fluoro-octyltrichlorosilane (FOTS) on an oxidized silicon wafer patterned with photoresist. Lifting off the resist provides an optically flat (invisible) pattern of hydrophilic SiO_2 rungs defined by a hydrophobic FOTS background (Figure 1). The three ARC devices used in this work are differentiated by the period (spacing) and duty cycle (rung width divided by rung period) of the hydrophilic rungs. All devices were characterized by the minimum vibration amplitude (ARC threshold) required to initiate transport of an 8 µL droplet of deionized water. This amplitude was measured with a laser Doppler-vibrometer, and a high-speed camera was used to record droplet transport. MATLAB software with custom scripts was used to determine the transport velocity of droplets from high-speed videos. All quantitative data is presented as mean± standard deviation.

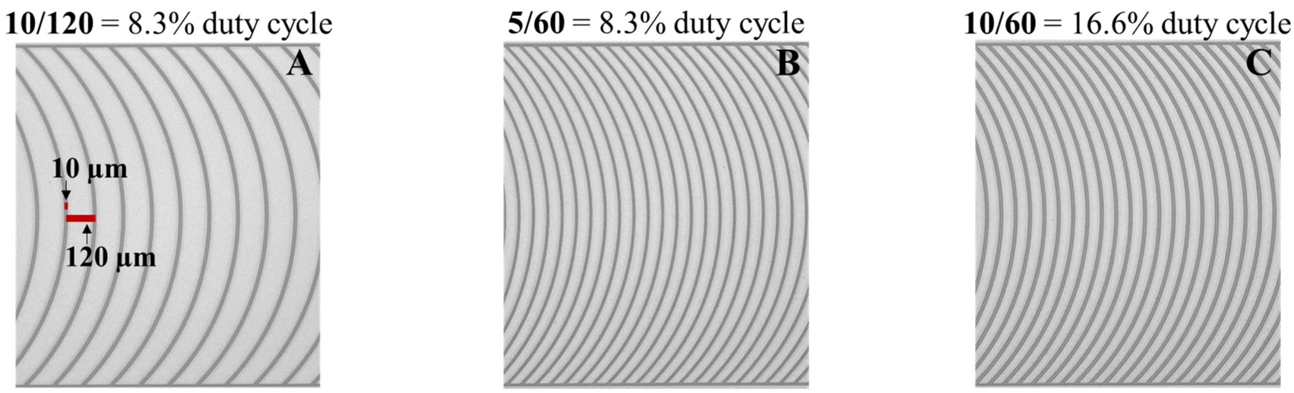


Figure 1: ARC tracks are described by their period and duty cycle. All ARC devices used in this work are unique combinations of wide (10 µm) and narrow (5 µm) rungs and large (120 µm) and small (60 µm) periods. Duty cycle is defined as the rung width divided by the period, where the rung is thought of as the working region of the track. Three ARC devices, consisting of a wide rung with a large period (10/120 or 8.3% duty cycle – A), a narrow rung with a small period (5/60 or 8.3% duty cycle – B), and a wide rung with a small period (10/60 or 16.6% duty cycle – C).

978-1-5090-5078-9/17/$31.00

RESULTS AND DISCUSSION

ARC Parameters and Transport Efficiency

The ARC threshold was measured for all ARC tracks over the functional frequency range of 30 to 100 Hz. We observed that all tracks exhibited a minimum ARC threshold at 80 or 90 Hz. The overall ARC threshold profile was also consistent for all ARC tracks, exhibiting a slight increase for decreasing frequencies below and a sharp increase for increasing frequencies above the frequency of minimum ARC threshold. This trend is also characteristic for previous ARC devices [2–4]. These profiles also show that the track with the large period (10/120) has the lowest ARC threshold for all frequencies except 90 Hz, which is the frequency of minimum ARC threshold for the small period tracks (Figure 2A). This observation seemed counterintuitive; the track with the large period has the most hydrophobic space between rungs, and therefore requires the most energy to expand the droplet edges to wet additional rungs.

In order to further understand these observations, we measured the area of the droplet during maximum wetting (e.g. when the contact line is fully expanded). These measurements confirmed that the edges of transported droplets were expanding the least on the 10/120 track at all frequencies except 90 Hz (Figure 2B). Furthermore, we initially hypothesized that the frequency of minimum ARC threshold was due to a resonance effect, and the wetting area would be largest at this frequency. These results indicate this relationship is not necessarily true, as the wetting area was actually the smallest at the frequency of minimum ARC threshold for all three tracks. These observations imply that the ARC threshold is correlated with the minimum wetting area required to initiate droplet transport. However, resonance effects are still a factor as local maxima were observed at 60 Hz for the 10/120 track and 50 Hz for the 10/60 and 5/60 tracks.

ARC Parameters and Transport Velocity

The motion of transported droplets was recorded at the ARC threshold for all tracks. Velocity is measured as the net horizontal displacement of the droplet centroid throughout one vibration cycle, multiplied by the frequency of the vibration. Therefore, these measurements describe the average velocity for each step of the droplet during transport. Interestingly, while the ARC threshold and wetting area profiles seem to be dependent on the period of the ARC track, the velocity profile, particularly at all frequencies above 40 Hz, appears to be determined by the duty cycle of the ARC track (Figure 2C). This observation is consistent with previous models of ARC transport [3], as the same duty cycle tracks have the same pinning ratio between leading and trailing edges. Even though the vibration amplitude is higher on the 5/60 track, the velocity and therefore net force, was the same on the 10/120 track at the ARC threshold.

The velocity of the 10/60 track exhibits a similar profile, but is shifted upward by about 3 to 5 mm/s at frequencies from 50 to 80 Hz. This observation seems to contradict the previous model for ARC transport, as the high duty cycle has a smaller leading to trailing edge pinning ratio (e.g. more of the trailing edge is pinned on the

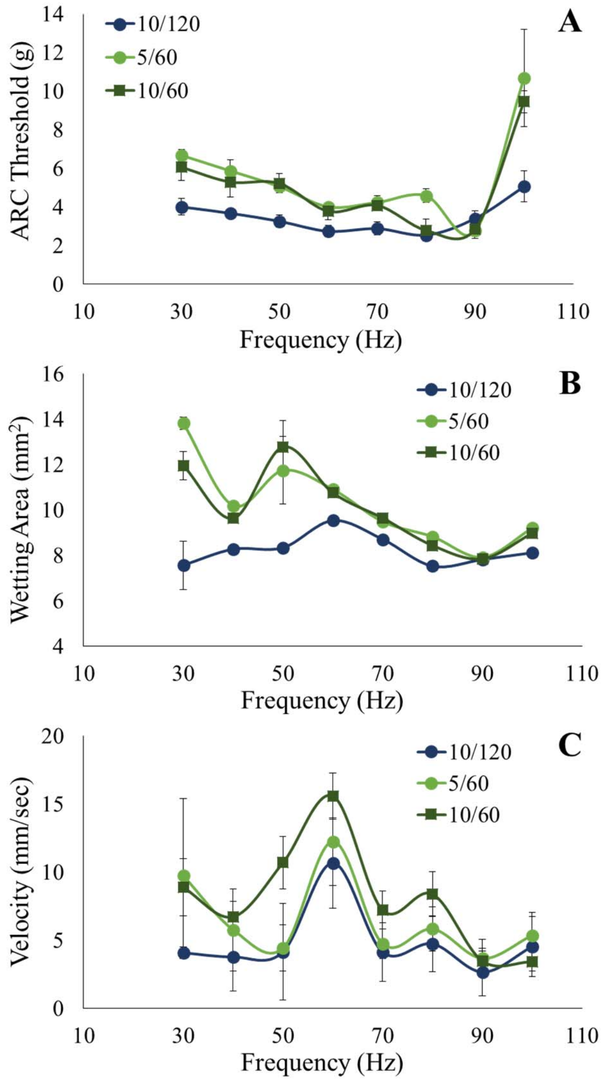


Figure 2: ARC design influences transport efficiency and velocity. The 5/60 and 10/60 tracks with the same period exhibit similar ARC threshold (A) and wetting area (B) profiles compared to the 10/120 track with a larger period. Meanwhile the velocity profiles appear to be determined by the duty cycle, as 10/120 and 5/60 tracks exhibit a similar profile in this case (C). Groups with the same duty cycle are indicated by the same marker shape (circle), and groups with the same period are indicated with a similar color (green).

track with higher duty cycle compared to the tracks with lower duty cycle). We hypothesize that this inconsistency is due to differences in shear stress between the rungs and droplet edges that were not previously considered. The rungs on the 10/60 track are twice as wide as the rungs on the 5/60 track, and, when expanded by the same amount (wetting area) would likely provide twice as much shear stress on the leading edge of the droplet (in the direction of transport).

The velocity profiles also resemble the wetting area profiles more closely than the ARC threshold profiles. With some exceptions, the velocity appears to be higher at frequencies with larger wetting areas. However, the obvious discrepancies between these two plots implies that other factors impact the relationship between wetting area and velocity. Among these factors, the frequency response of droplet to vibrations is likely the key. The effects of this response are exhibited by the resulting differences in aspect ratio and height of the droplet (data not shown) at different frequencies. In future work we look to develop a model that can account for all of these factors.

Vibration Amplitude and Transport Velocity

Initially, we hypothesized that droplet velocity was related to the frequency of the applied vibration. We assumed the droplet would advance by a step of one rung each cycle, and these steps would be faster with higher frequencies. The velocity profiles observed in Figure 2 prove that this hypothesis is incorrect, and that the transport velocity appears to be influenced by the amount of wetting, or expansion of the droplet edges. In order to better understand the factors influencing transport velocity, we also recorded the motion of droplets driven on the most efficient 10/120 track with vibrations that were 0.5 g below, 0.5 g above, and 1 g above the threshold amplitude for this track.

We observed that vibrations 0.5 g below the threshold amplitude provided an average velocity of essentially zero (Figure 3A). Although it was rare, the droplets actually took a step forward throughout some vibration cycles with a sub-threshold amplitude (indicated by the small standard deviation of these data points). This observation indicates that with vibrations below the ARC threshold the droplet edges are expanding sufficiently to contact more rungs and additional conditions must be met to provide net transport. Increasing the vibration amplitude 0.5 g above the ARC threshold shows that the transport velocity increased at some frequencies, particularly at 60 Hz, but not for all frequencies. Further increase of the vibration amplitude to 1 g above the ARC threshold also increased transport velocity, but over a much larger frequency range (Figure 3A).

These results indicate that the transport velocity is correlated to the vibration amplitude, but this relationship is not linear and seems to be frequency dependent (e.g. the velocity increase is different at each frequency for the same change in amplitude). The differences in frequency are likely due to the droplet frequency response (i.e. height and aspect ratio), as discussed earlier, and will require further experimentation and analysis to fully understand. However, looking at droplets vibrated with different

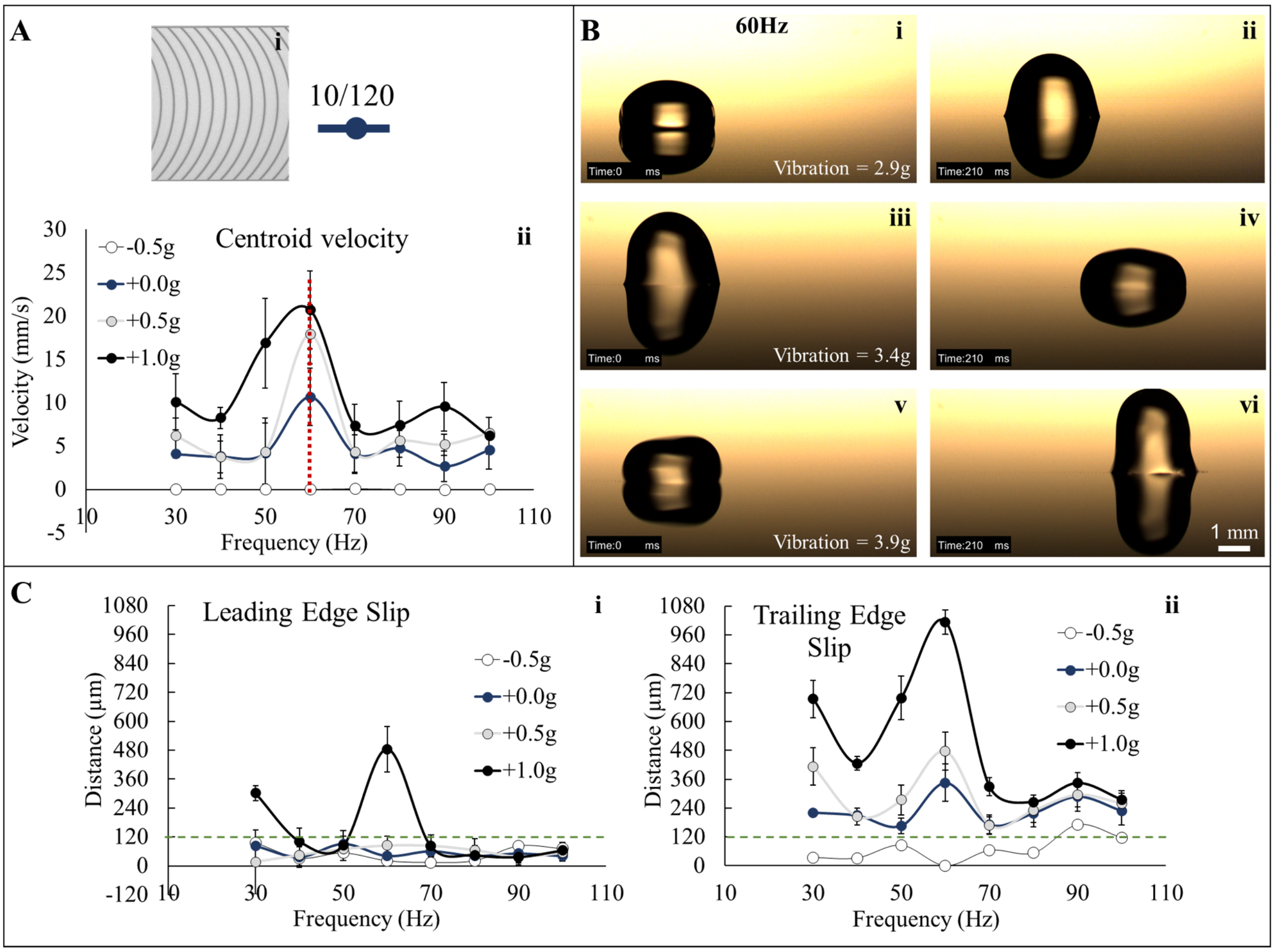


Figure 3: Transport velocity is correlated with vibration amplitude. The transport velocity on the most efficient track (Ai) was measured for vibrations 0.5 g below, 0.5 g above, 1.0 g above, and at the ARC threshold. No net transport was observed at vibrations below the ARC threshold, but transport velocity increases, although non-linearly, with vibration amplitude (Aii). Images from transport recordings (B) demonstrate how droplet transport is affected by vibration amplitude at 60 Hz (red line in Aii). Increased wetting results in greater transport velocities as the leading edge remains pinned (Ci), but slip of the trailing edge (Cii) increases. Red dashed line in Aii indicates frequency of images in B and green dashed lines in C indicate the distance of one rung period.

amplitudes (Figure 3B), we observe that as the amplitude is increased the droplets become flatter, contacting more rungs, during wetting and taller, contacting fewer rungs, during de-wetting phases. We also see that the leading edge remains pinned (does not slip) for all data points expect +1 g vibrations at 30 and 60 Hz, while the trailing edge slip increases as amplitude is increased (Figure 3C). The slip profiles of the trailing edge are also very similar to the transport velocity profiles, indicating the correlation between the two. Furthermore, the maximum velocity (~21 mm/s) of droplets measured here is 2 to 3 times faster than the maximum velocity measured on electrowetting-based systems [5].

Transport is determined by quantized step probability

Looking more closely at the movement of the droplet edges, we noticed that the movement is not continuous, but rather the edges jump from rung to rung. This implies that droplet advancement is quantized, or, in other words, the droplet advances by an integer number of rungs each vibration cycle. We also notice that the droplets do not advance by the same number of rungs with each step (note the standard deviation in Figure 3). From measurements of edge movement, we are able to estimate the probability that the droplet will advance by a given number of rungs (Figure 4). We hypothesize that this distribution results from a competition of the pinning forces (acting to hold the droplet edges apart on the rungs) and the droplet forces (acting to pull the droplet edges together). While the pinning forces, determined by the ARC design, are always the same, the droplet forces are determined by a number of factors (such as vibration frequency and amplitude, momentum, inertia, and internal flow of the droplet) and may be different for each vibration cycle. These effects result in a probability distribution for each frequency-amplitude combination. Increasing amplitude also shifts this distribution towards a high number of rungs (e.g. the droplet becomes more likely to take a larger step). Data is shown for 60 Hz (Figure 4) but these results are consistent over all frequencies measured in this study. Furthermore, this probability distribution is in agreement with the measured transport velocity at all frequency-amplitude combinations.

CONCLUSION

ARCs are a type of DMF system that transports droplets on a passive, microfabricated surface pattern through the application of orthogonal vibrations. Here, we demonstrate that the velocity of droplet transport can be controlled by both the ARC pattern and applied vibration parameters. We also discovered that the velocity is ultimately determined by the probability of advancing by a discrete number of rungs, or steps, on the ARC pattern. These measurements show droplet velocity is faster on ARCs than on electrowetting based systems, and future work looks to apply these findings towards a lab-on-a-chip system for low-cost, rapid analysis of DNA.

ACKNOWLEDGEMENTS

This work was supported by National Science Foundation grant ECCS-1308025 "Droplet Ratchets: Low Cost Digital Microfluidics". HRH would like to acknowledge the National Defense Science and Engineering Graduate Fellowship (NDSEG) for their support of this work. Fabrication of ARCs was performed at the Washington Nanofabrication Facility (WNF), a National Nanotechnology Coordinated Infrastructure (NNCI) site at the University of Washington, which is supported in part by the National Science Foundation (awards 1542101, 1337840 and 0335765), the Washington Research Foundation, the M. J. Murdock Charitable Trust, Altatech, ClassOne Technology, GCE Market, Google and SPTS.

REFERENCES

[1] Holmes HR, Böhringer KF. Transporting droplets through surface anisotropy. Microsystems & Nanoengineering 2015;1.

[2] Holmes HR, Gomez AE, Böhringer KF. Timing and synchronization of droplets on ratchet conveyors. 2016 IEEE 29th International Conference on Micro Electro Mechanical Systems (MEMS), IEEE; 2016, p. 796–799.

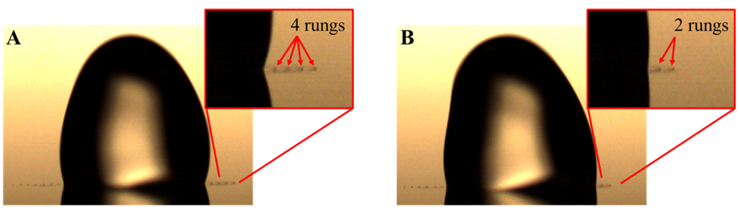
[3] Duncombe TA, Parsons JF, Böhringer KF. Directed Drop Transport Rectified from Orthogonal Vibrations via a Flat Wetting Barrier Ratchet. Langmuir 2012;28:13765–70.

[4] Duncombe TA, Erdem EY, Shastry A, Baskaran R, Böhringer KF. Controlling Liquid Drops with Texture Ratchets. Adv Mater 2012;24:1545–50. doi:10.1002/adma.201104446.

[5] Jang L-S, Hsu C-Y, Chen C-H. Effect of electrode geometry on performance of EWOD device driven by battery-based system. Biomed Microdevices 2009;11:1029..

CONTACT

*K.F. Böhringer, tel: +1-206-2215177; karlb@uw.edu



	Number of Rungs Advanced at 60Hz							C
Amplitude	0	1	2	3	4	5	6	Weighted Mean x 60Hz (mm/s)
-0.5g	1.00	0.00	0.00	0	0	0	0	0.0
+0.0g	0.02	0.32	0.55	0.11	2.1×10^{-3}	3.2×10^{-6}	3.8×10^{-10}	12.6
+0.5g	1.7×10^{-3}	0.07	0.44	0.42	0.06	1.3×10^{-3}	3.7×10^{-6}	17.8
+1.0g	4.5×10^{-3}	0.06	0.28	0.41	0.20	0.03	1.7×10^{-3}	20.6

Figure 4: Droplet edges are quantized and advance according to a probability distribution. Droplet edges jump from rung to rung with some probability. For example, two images from the same video of a transported droplet show the leading edge sometimes slips back by four rungs (A – slower transport) and sometimes only two rungs (B – faster transport). The mean advancement of the droplet provides a probability distribution that predicts how likely the droplet will advance by an integer number of rungs (C). This distribution correlates to the transport velocity of the droplet.