Supporting Information (SI) for: Sound Wave Activated Nano-Sieve (S.W.A.N.S) for Enrichment of Nanoparticles†

Ruhollah Habibi
LMS, Monash University

Adrian Neild*
LMS, Monash University

I. Theory and numerical models

The methodology of the numerical simulations and theory behind them are established on the basis Habibi et al.'s work.[1] The application of the perturbation theory into time-dependent oscillating pressure, velocity and density fields is explained in that work. After plugging them into the continuity and Navier-Stokes equations and taking time average, the second-order pressure integrated over the surface of the particle provides the force, $\boldsymbol{F}$, applied on the particle:

$$\langle \boldsymbol{F} \rangle = \int_{S_0} \frac{\rho_0}{2} \langle v_1^2 \rangle \boldsymbol{n} d\boldsymbol{S} - \int_{S_0} \frac{1}{2\rho_0 c_a^2} \langle P_1^2 \rangle \boldsymbol{n} d\boldsymbol{S} - \int_{S_0} \rho_0 \langle (\boldsymbol{n} \cdot \boldsymbol{v_1}) \boldsymbol{v_1} \rangle d\boldsymbol{S}\,, \tag{1}$$

Where ρ_0 is the fluid density at rest, c_a the speed of sound in the fluid and v_1 and P_1 are the first-order velocity and pressure terms, respectively. Here, $\boldsymbol{n}$ represents the normal vector of the particle's surface, $\boldsymbol{S}$ and the integration is performed over the initial surface, S_0. $\langle\rangle$ denotes the time average operator.

Similar to the referenced work, the finite element method (FEM) model was constructed in COMSOL Multiphysics® 5.1 to investigate acoustic radiation forces on micro and nanoscale polystyrene particles.

Firstly, the frequency effect on the acoustic radiation force on a single 10 μm polystyrene particle was conducted in a 2D antisymmetric space that provided the primary force results with distinguishable regions. The basic parameters of the FEM model and materials properties are given in Table S1 under **2DAxi-1P**.

Similarly, the primary, total and consequently secondary (Bjerknes) acoustic radiation forces on a nanoparticle were investigated in a 2D antisymmetric space FEM model of two particles, a 10 μm as the microparticle and one 500 nm as the nanoparticle, positioned around an anti-node with

*Corresponding author: Laboratory for Micro Systems, Department of Mechanical and Aerospace Engineering, Monash University, Clayton, Victoria 3800, Australia.; E-mail: adrian.neild@monash.edu

Table S1: *Basic parameters of the FEM models that were simulated in this work. Material data are obtained from COMSOL material library otherwise stated. The values of parameters are given for each FEM model, single 10 μm polystyrene particle under 2DAxi-1P, the interaction of one microparticle and one nanoparticle under 2DAxi-2P and a cluster of microparticles as the packed bed under 2D-MMP.*

Parameter	Symbol	Unit	**2DAxi–1P**	**2DAxi– 2P**	**2D-MMP**
Fluid Domain					
Water					
Density	ρ_f	kg m^{-3}	1000	1000	1000
Speed of sound	c_f	m s^{-1}	1500	1500	1500
Domain height	L	μm	100	40	$\lambda \times 3$
Domain width	W	μm	50	15	$\lambda \times 2$
Frequency	f	MHz	15∼105	15∼105	15
Wavelength	λ	μm	c_f/f	c_f/f	100
Wavenumber	k	μm	$2\pi/\lambda$	$2\pi/\lambda$	$2\pi/\lambda$
Acoustic pressure amp.	P_0	kPa	100	100	100
Mesh size range	e_f	μm	0.03∼1	0.02∼0.6	0.01∼1
Curvature factor		-	0.3	0.1	0.15
Max. mesh growth rate		-	1.05	1.08	1.3
Solid Domain					
Polystyrene					
Density[3]	ρ_{ps}	kg m^{-3}	1050	1050	1050
Modulus of elasticity[a]	E_{ps}	GPa	3.60	3.60	3.60
Poisson ratio[4]	ν_{ps}	-	0.35	0.35	0.35
Domain dimensions:					
Microparticle diameter	d	μm	10	10	$0.31 \times \lambda$
Microparticle radius	R	μm	5	5	d/2
Nanoparticle diameter	d_{NP}	μm	n/a	0.5	n/a
Nanoparticle radius	R_{NP}	μm	n/a	0.25	n/a
Gap between particles	Gap	μm	n/a	$\lambda/200$	0
Mesh size range	e_s	μm	0.03∼0.5	0.02∼2	0.01∼R/10
Curvature factor		-	0.2	0.15	0.3
Max. mesh growth rate		-	1.1	1.05	1.3
Fluid-Solid interface					
Mesh size range	e_1	μm	0.03∼0.2	0.004∼0.02	0.01∼0.1
Curvature factor		-	0.15	0.15	0.15
Max. mesh growth rate		-	1.05	1.05	1.05

[a] Calculated from Bulk Modulus (K_{ps}) as $E_{ps} = 3K_{ps}(1 - 2\nu_{ps})$ from ref. 4 and 5.

the normalised *Gap* of $\lambda/200$ with frequency range of 15 to 105 MHz (that corresponds to the microparticle's normalised size of d/λ from 0.1 to 0.7). The values of parameters and properties of this stage of the simulation are presented under **2DAxi-2P** in Table S1.

To investigate the presence of multiple microparticles and the shape of force field around them when at a frequency in region B and close to resonance, a 2D space dimension was used. To represent a packed bed, the *Gap* between microparticles was considered zero. The forces on 500 nm particles were computed based on Gor'kov[2] formulation and due to the varying scale of the force vectors, for the purpose of visualisation, all vectors were normalised that still provide information on the direction of force field. The parameters details of this section are given in Table S1 under **2D-MMP**.

II. Operation sequence

The sequences of the operation of SWANS system is shown in Fig. 1b of the main article where channels are washed with distilled water and then 2% PEG water solution as the first step *(i)*. This is to wet the channels and to ensure no large debris would be present in the test channel, suspensions are filtered at the inlet. The second stage is the loading of the microparticles suspended in 2% PEG water solution to create the packed bed *(ii)*. After the completion of packed bed loading, when the length of the packed bed covers IDT's aperture and beyond it providing packed bed's stability at resonance, the solution of nanoparticles at desired concentration and flowrate is loaded to the microchannel *(iii)*. The pores between microparticles are large enough to provide a smooth flow of the nanoparticles. When the collection of the nanoparticles is in demand, IDTs are activated at a certain frequency that generates the surface acoustic wave (SAW) and consequently entraps nanoparticles *(iv)*. The collected batch of nanoparticles in the upstream has a high concentration now and can be released to the downstream on demand by de-energising of the IDTs *(v)*.

III. Effect of hydrodynamic resistance on the collection

The packed bed creates a hydrodynamic effect on the flow and the passage of the nanoparticles, increasing the resistance against the flow, however, due to the size of the pores (approximately about 4 μm), 500 nm can pass freely. There might be some random entrapments of nanoparticles at the boundary of those pores in long run, however, its effect is very minor and can be neglected in comparison to the collection due to primary and secondary forces applied on the nanoparticles. The slopes of black dotted and dashed black lines in Fig. S2 as an indication of intensity growth over the SAW activation period (30 seconds here) are 87% for 62.5 MHz and 193% for 75 MHz, respectively.

IV. Capturing efficiency evaluation

To evaluate system performance at capturing of nanoparticles, the intensity of fluorescent nanoparticles at the downstream were integrated over the selected area. Upon activating the SAW and after the transient time, the intensity level is stabilised and steady for optimised frequencies. Ideally, if all nanoparticles are trapped at the upstream, the grayscale intensity of light at the downstream should be zero, equivalent to pure black(Fig. S5). The difference of the area between actual intensity level to the black reference line can represent the fraction of passed particles. However, as it can be seen from Fig. S5b, the grayscale intensity level even at the locations that there is no particle (outside the channel for example) is not zero. This background intensity, possibly due

to the reflection and refraction of fluorescent light into the PDMS, is set as the threshold. Thus, the efficiency is calculated as the ratio of the area highlighted as captured to the total area of the rectangle below the initial level and this background intensity threshold.

References

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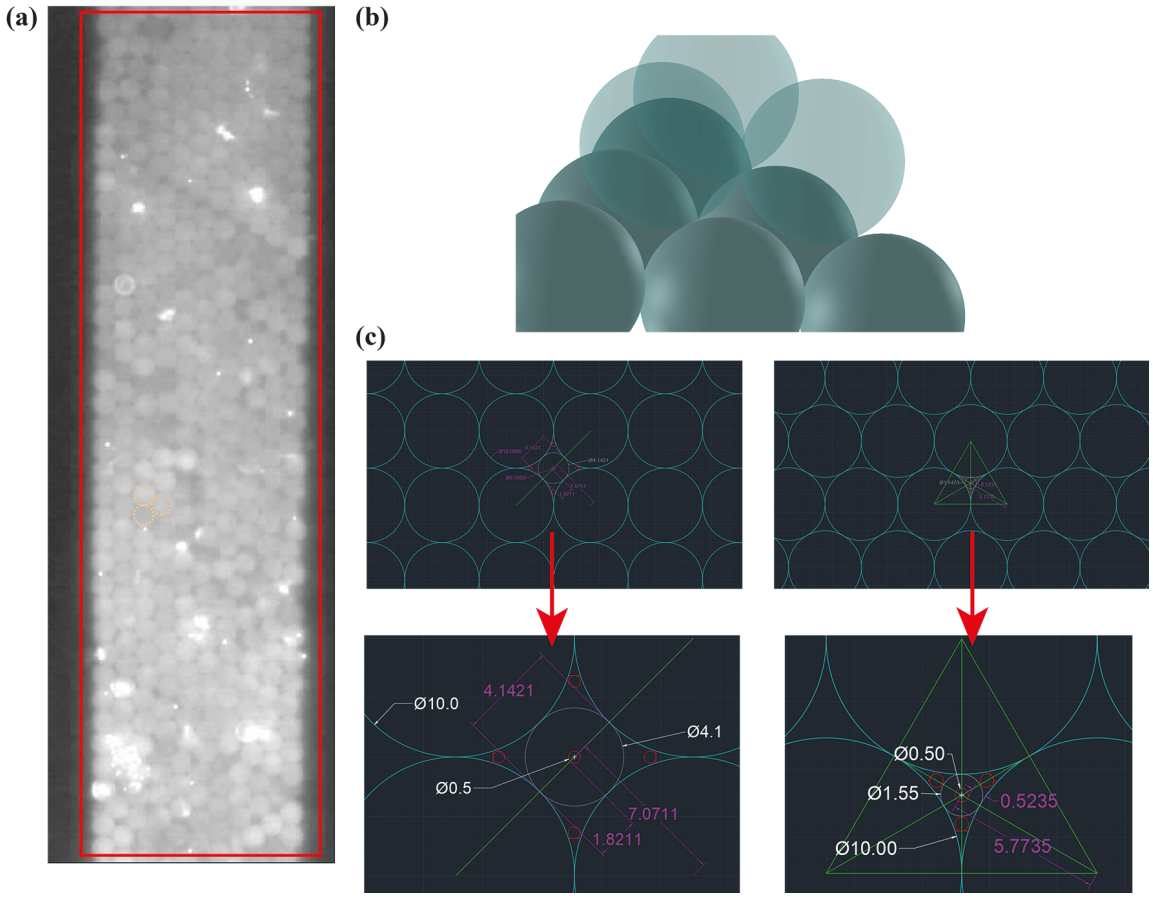

Fig. S1: *(a)Caption of the packed bed at a relatively higher magnification shows that beads are well packed in a honeycomb-like pattern (the ideal packing scenario) (b) Spheres in an ideal packed scenario and their cross section in different planes (c) where provide largest (left) and narrowest (right) passage for red nanoparticles. Dimensions are in micrometer. The 'pore' size is about 41% of the microparticle (MP) diameter and the passage between spheres are about 15.5% of the MP's size. That brings the gap between MP and NP down to 500 nm. In this work it is about 1/50 of the wavelength.*

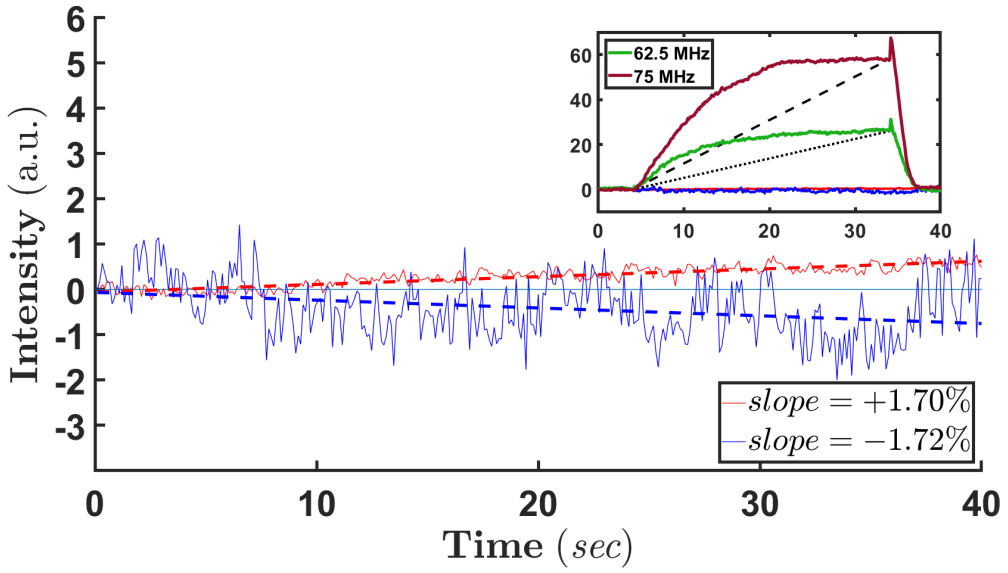

Fig. S2: *Instantaneous intensity level at the upstream of the channel (width 94 μm)* ***without*** *activating the SAW, at two extreme cases that have the highest average linear intensity growth (both ascending and descending). When compared with intensity level growths by energised SAW (here are shown for 2 different frequencies of 62.5 and 75 MHz activated for 30 seconds in the inset), the intensity change due to hydrodynamic effects is insignificant and thus negligible.*

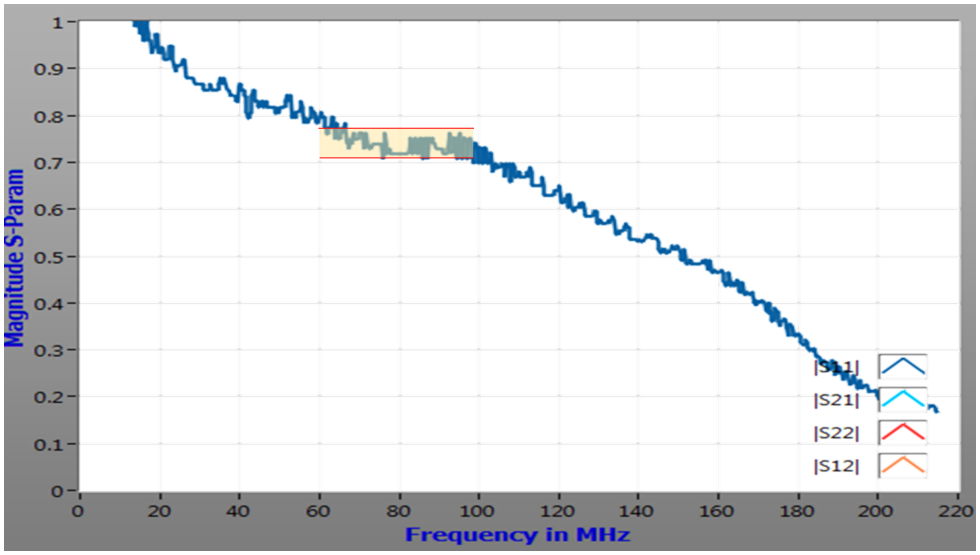

Fig. S3: *The |S11| parameter of the IDT, that was used in the frequency characterisation, is nearly constant with no significant change within the range of 60 - 90 MHz. This asserts that the optimum frequencies, where the nanoparticle collection is higher, depend on the physics of the interaction between nanoparticles and the microparticles of the packed bed rather than the chirped IDT's response. S11 parameter is obtained using PowerSAW F-20 (BelektroniG, Germany) signal generator.*

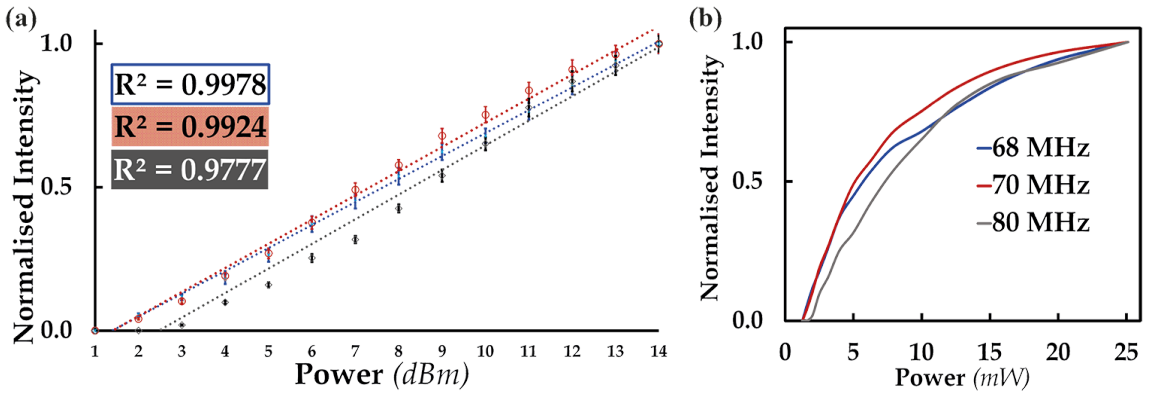

Fig. S4: ***(a)*** *The normalised intensity gains at different frequencies show linear compliance with power level in dBm (with R^2 shown and linear regression p-value is <0.001 for three data sets), thus a (b) logarithmic leaning against power levels in mW.*

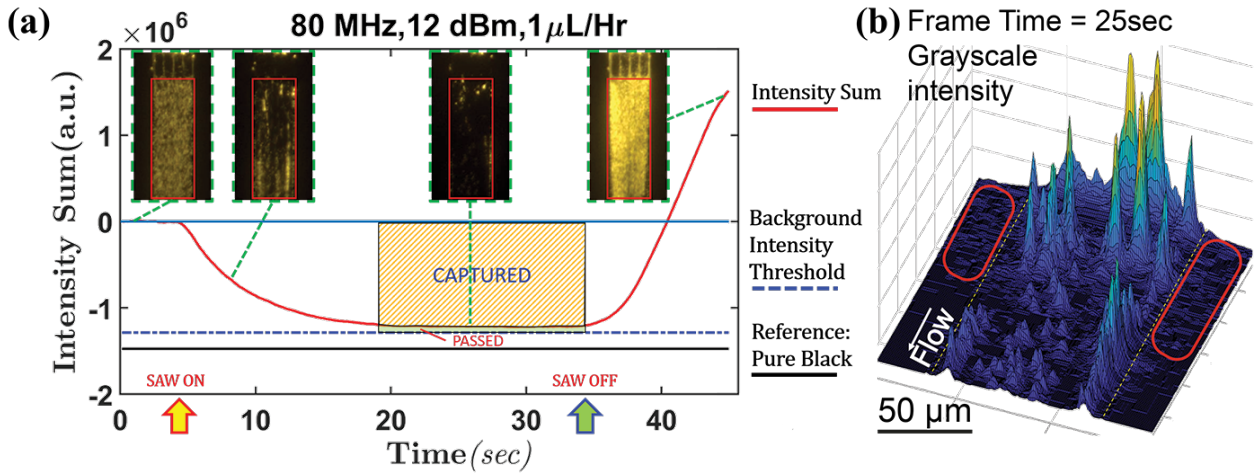

Fig. S5: *(a)Integrated intensity of the selected region at the downstream were considered to represent the population of passed nanoparticles. After the intensity stabilised, the differenced of intensity with the initial level shows the fraction that captured. (b)The background area is not zero (pure black) even at locations that no fluorescent nanoparticle is present such as outside of the channel. This intensity is defined as the threshold instead of the black background reference.*