Process Model Identification for Optimizing Particle-to-Part Selectivity during Ultrasonic Parts Cleaning

Osama Khalil, John Deem, Iordan Iordanov, Ardeshir Sidhwa Ph.D., Matthew House, David Zuck

QUANTUM GLOBAL® TECHNOLOGIES, LLC

Phoenix, AZ ✧ Quakertown, PA

Introduction

- Meeting defect limitations is a persistent challenge in chamber component parts cleaning as technology nodes continue to scale down. Particles, which are a target of the final stages of cleaning, create killer defects at the component level, and can be expected to severely impact product yields at sub-10 nm technology nodes.
- Ideal final stage cleaning removes particles that are loosely or partially adhered to a part substrate or coating, without generating particles from pitting the substrate material itself.
- Realistically, ultrasonic cleaning can quickly remove adhered particles but can adversely impact the substrate material.

The present work deals with characterizing ultrasonic cleaning by:

1. Mapping spatial acoustic energy distributions under different frequencies, supplied power, measurement probes, and tank designs
2. **Automating experiments for process model identification of particle removal dynamics**
3. Computer simulation-based design of ultrasonic tanks

Process Modeling

The goal of "grey" process model system identification is to identify the relationship between inputs and outputs of a system by applying both first principles and experimental data. In understanding particle removal dynamics during ultrasonication, the modeling variables will be defined as:

y =output variable=particle count by liquid particle counter (LPC)

u =input variable=ultrasonic power (on/off)

Data indicates 2nd-order and single zero behavior [1].

Ordinary differential equation in time domain:

$$T_D{}^2\frac{d^2y(t)}{dt^2}+2\xi T_D\frac{dy(t)}{dt}+y(t)=K\left(\alpha\frac{du(t)}{dt}+u(t)\right)$$

Following the Laplace Transform to the gain-time constant form for a second-order linear system in the complex s domain gives the transfer function g(s) for the system:

$$\frac{u(s)}{y(s)}=g(s)=\frac{K(\alpha s+1)}{T_D^2s^2+2\xi T_D s+1}$$

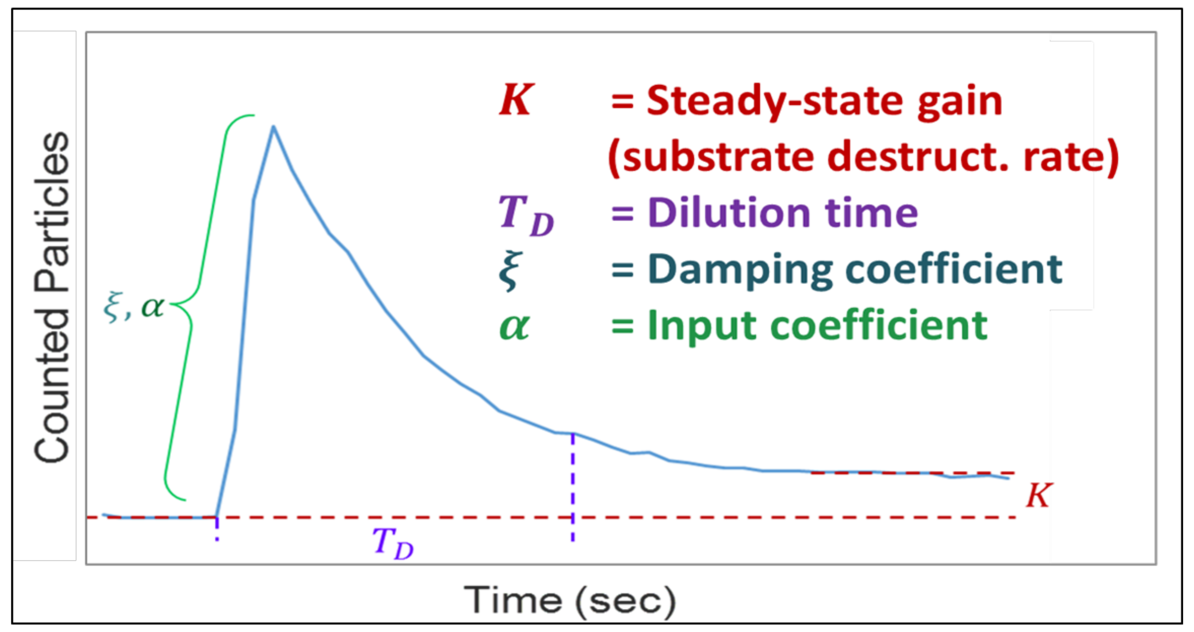

Figure 1: Sample LPC data demonstrating how transfer function parameters indicate measurable quantities (i.e. substrate destruction rate, tank dilution time, maximum particle removal rate)

Results

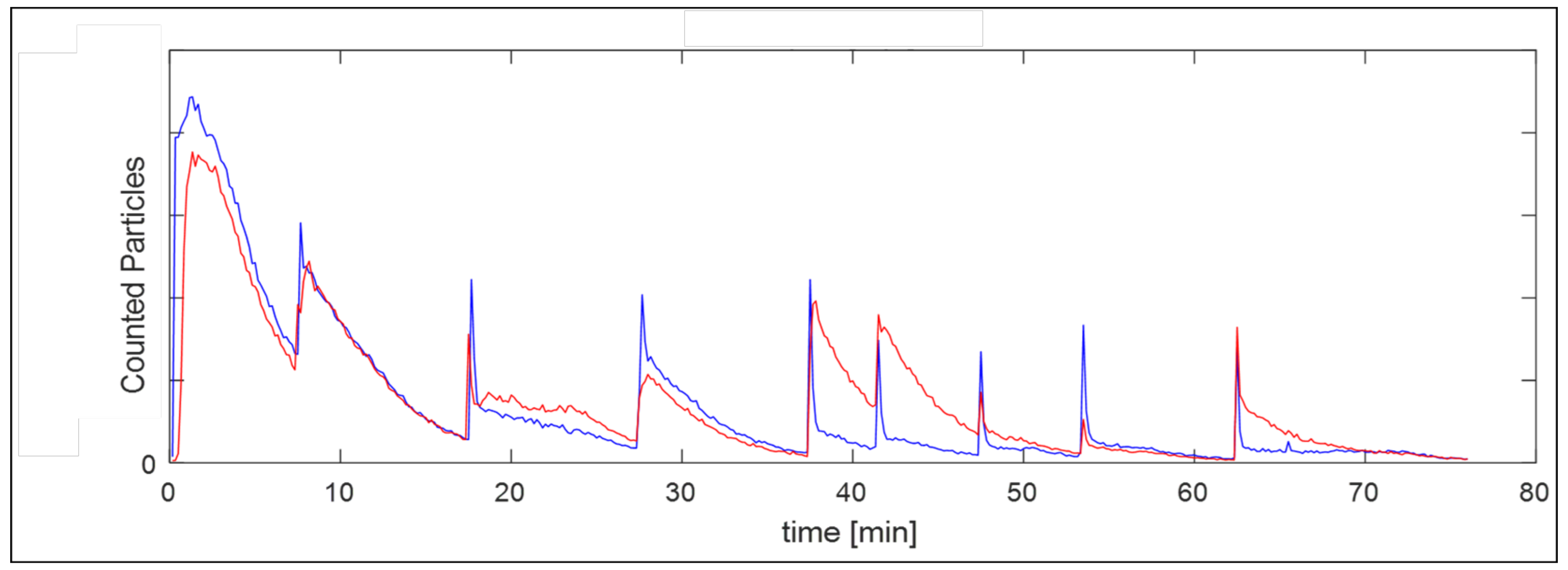

Figure 2: LPC data for two replicate ultrasonic pulse experiments using the same pseudo-random binary sequence of ultrasonic power signals on a textured aluminum sample.

Partial results are shown in Figure 2, which plots particles counted as the output to an input sequence of ultrasonic power cycles. Figure 2 also demonstrates the remarkable repeatability of this experiment between two entirely independent replicates.

Transfer functions can only be used to describe a process that is linear time-invariant (LTI)[2]:

1. The relationship between input and output is a linear map
2. If we apply an input to the system now or T seconds from now, the outputs would be identical

In our case, peaks diminish with each successive ultrasonic power activation:

- The LPC-ultrasonic system is not LTI, so no single model can accurately represent serial cleans
- Repeatability testing demonstrates that reliable models could be generated for every nth ultrasonic power activation

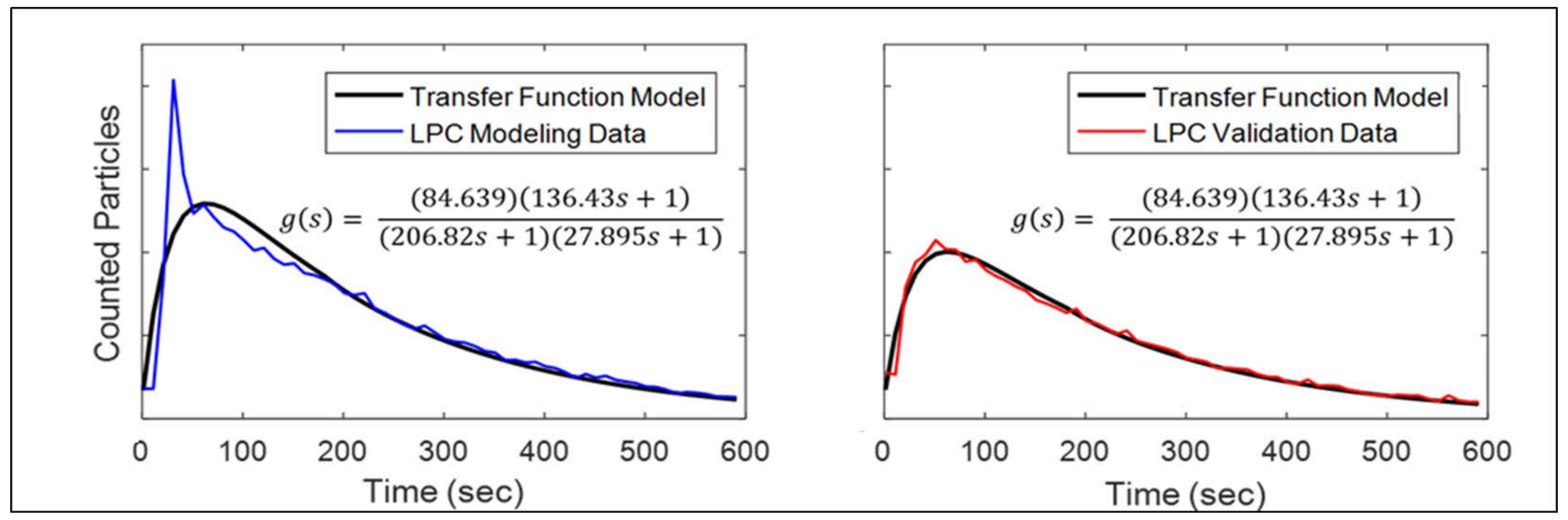

Figure 3: Modeling data (left) and validation data (right) extracted from data in Figure 2 for ultrasonic power activation n = 4. The same transfer function generated from modeling data is applied to the validation and demonstrates a strong fit.

Strong results from repeatability studies and model validation led to the design of an automated experiment with which large set of data are captured from the LPC-ultrasonic system. Captured data is for extensive modeling and model validation to create a large library of models to have an operating model to better describe particle removal dynamics under universal conditions.

Conclusions

Understanding particle removal dynamics will be critical in continuing to meet the ever-tightening defect limitations of shrinking semiconductor node dimensions. Data from the present work have shown that particle removal is repeatable and can be modeled using system identification methodology. Automating these experiments help build a large library of models to have an operating model to better describe particle removal dynamics under universal conditions. These models will facilitate design optimization of ultrasonic rinse tanks as a part of QuantumClean's continued mission to keep pace with Moore's Law.

Related Work

A full characterization of ultrasonication for final parts cleaning goes beyond particle removal dynamics. The next fundamental component of characterization is understanding what factors affect the spatial uniformity of ultrasonic energy density. Figure 4 shows two examples of ultrasonic energy mapping data from a QuantumClean ultrasonic rinse tank. Future work will be to use models from this study and energy density distribution data to perform computer simulation-based pilot designing of ultrasonic tanks to optimize bulk particle removal (Figure 5), and energy density uniformity.

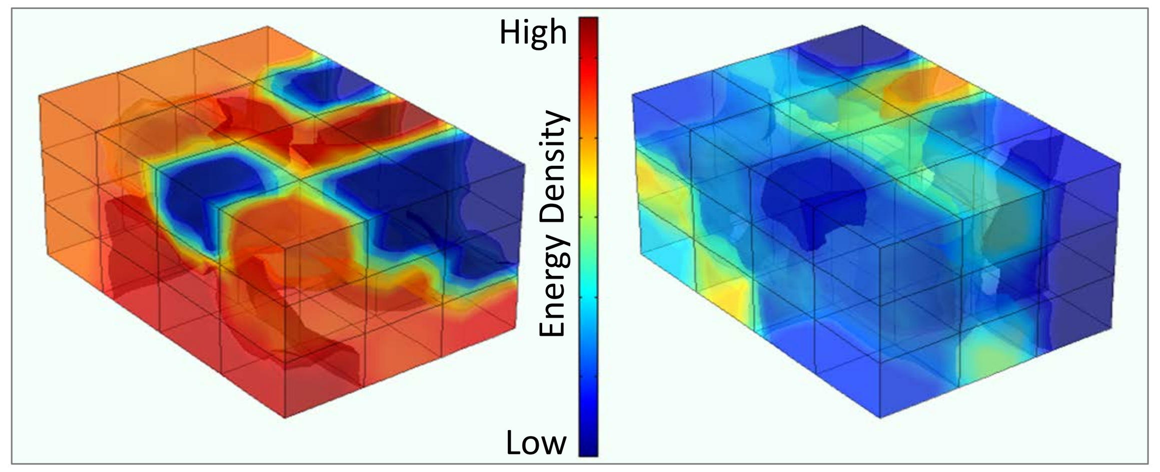

Figure 4: Three-dimensional representation of ultrasonic (acoustic) energy density throughout the volume of an ultrasonic rinse tank

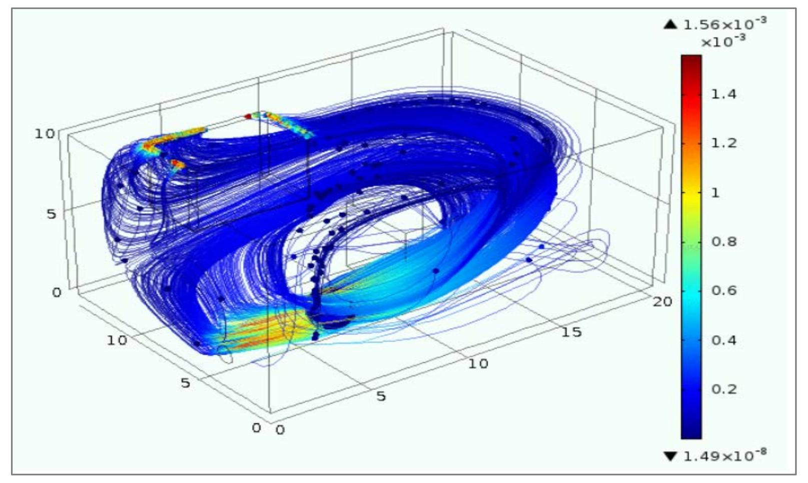

Figure 5: A time-variant finite element simulation of particle trajectories within the flowing fluid space of an ultrasonic rinse tank

References

[1] Bequette, B.W. (2002). Process Control: Modeling, Design and Simulation.

[2] Hespanha, J.P. (2009). Linear Systems Theory, 21-25.

Contact

Osama Khalil
osama.khalil@quantumclean.com
Quantum Global Technologies, LLC
Phoenix-East Facility
3925 E. Watkins St., Ste 100
Phoenix, AZ 85034

QUANTUM GLOBAL® TECHNOLOGIES, LLC

QUANTUM CLEAN®

SPCC 2017
Surface Preparation and Cleaning Conference
March 28-29 Austin, TX