

# Acoustic and Vibration Fields During Photopolymerisation: Bubble Motion, Particle Organisation and Cure Perturbation

*Separating intentional acoustic assembly from unintended vibration so that field effects can be measured and controlled*

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## Abstract

Acoustic or mechanical excitation applied during photopolymerisation can reorganise bubbles, particles and interfaces while simultaneously perturbing heat transfer and cure kinetics. The engineering problem is therefore to separate genuine field-driven organisation from artifacts caused by vibration, cavitation or thermal drift. ER-355 combines force and acoustic-field characterisation with high-speed imaging, thermal measurement and post-cure microstructural analysis. Frequency, amplitude and boundary-condition sweeps are interpreted against particle-response and bubble-dynamics timescales. Qualification is framed around reproducible structure formation and cure uniformity, with explicit rejection of operating regions in which cavitation, heating or fixture resonances dominate the observed response.

**Keywords:** acoustic field; ultrasound; particle assembly; bubble dynamics; vibration; photocure

## 1. Qualification problem: acoustic forcing during cure

The practical boundary of acoustic forcing during cure is defined by decisions, not by the presence of the mechanism alone. This review tests whether acoustics are a controlled assembly step or an uncontrolled vibration disturbance, minimum organisation time before exposure, and field amplitudes that improve orientation without bubble damage while retaining acoustic contrast factor, Stokes number, and Strouhal-like timing ratio as independent descriptors of the tested state. [1]

### 1.1 Scope boundary.

ER-355 owns imposed acoustic/vibration response. ER-356 and ER-357 own electric- and magnetic-field organisation, ER-358 shear-induced alignment, and ER-360 multiphysics validation; this review is limited to acoustic forcing, particle/bubble response and cure perturbation.

## 2. Governing balances for acoustic forcing during cure

Acoustic organisation is evaluated with relations that separate field forcing from particle response and exposure timing.

*primary acoustic radiation forces move inclusions toward pressure nodes or antinodes depending on acoustic contrast*

*secondary Bjerknes forces can drive bubble-bubble interactions*

*streaming creates steady advection that can compete with intended standing-wave assembly*

Their combined use separates deliberate particle organisation from vibration-induced disturbance or bubble-mediated damage.

## 3. Regime boundaries for acoustic forcing during cure

In the acoustic case, the table separates conditions suitable for controlled organisation from those requiring disturbance or bubble-risk testing.

Table 1. Regime indicators for acoustic/vibration response.

| Indicator                  | Engineering meaning                                              | Use                                                                                                                                                                                                                                                                                                    |
|----------------------------|------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| acoustic contrast factor   | migration direction expected for particles in the acoustic field | Use acoustic contrast factor to decide whether 'whether acoustics are a controlled assembly step or an uncontrolled vibration disturbance' is an interpolation within evidence or an extrapolation beyond it; the indicator captures migration direction expected for particles in the acoustic field. |
| Stokes number              | particle inertia relative to viscous response                    | Use Stokes number to decide whether 'minimum organisation time before exposure' is an interpolation within evidence or an extrapolation beyond it; the indicator captures particle inertia relative to viscous response.                                                                               |
| Strouhal-like timing ratio | acoustic organisation time relative to cure-arrest time          | Use Strouhal-like timing ratio to decide whether 'field amplitudes that improve orientation without bubble damage' is an interpolation within evidence or an extrapolation beyond it; the indicator captures acoustic organisation time relative to cure-arrest time.                                  |

Organisation results are accepted only for field, particle-response, and timing combinations demonstrated without damaging side effects.

## 4. Couplings that move the acoustic forcing during cure

Ultrasound can align or concentrate fibres before cure arrests them. [1]

Bubbles can oscillate strongly and locally perturb conversion or scatter light.

Acoustic absorption introduces heating that changes kinetics independently of mechanical forcing.

## 5. Failure signatures and false diagnoses

The relevant defects are unintended nodal banding or concentration gradients, bubble coalescence, translation or collapse damage and loss of alignment because cure begins before the acoustic field reaches steady organisation. A diagnosis is credible only when high-speed imaging of bubble and particle motion, hydrophone or calibrated pressure-field mapping or temperature monitoring during sonication identifies the corresponding branch rather than simply confirming that the part has changed. No single Table 2 row closes attribution. The diagnosis must remain coherent when the other interventions are applied as counter-tests.

Table 2. Failure-mode discrimination for acoustic/vibration response.

| Failure mode                                                                                | Observable signature                                        | Discriminating evidence                                                    |
|---------------------------------------------------------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------------------------|
| unintended nodal banding or concentration gradients                                         | high-speed imaging of bubble and particle motion            | sweep frequency through and away from resonance at matched acoustic energy |
| bubble coalescence, translation or collapse damage                                          | hydrophone or calibrated pressure-field mapping             | compare standing-wave and traveling-wave configurations                    |
| loss of alignment because cure begins before the acoustic field reaches steady organisation | temperature monitoring during sonication                    | run acoustics without illumination and illumination without acoustics      |
| apparent acoustic effect that is actually thermal                                           | post-cure orientation tensors from microscopy or tomography | vary delay between field application and cure                              |

## 6. Measuring acoustic forcing during cure with traceable uncertainty

The three diagnostic measurements in Table 2 are treated as complementary rather than redundant. A common specimen history or matched state is required before they are compared. Rather than reduce acoustic forcing during cure to one surrogate, the analysis combines separate monitoring of cure timing with independent resolution of acoustic radiation force and bubble interaction; during metrology of acoustic forcing during cure, steady streaming is resolved against cure timing. A separate an uncertainty-controlled perturbation of steady streaming is used to challenge that interpretation, making disagreement between the two routes visible instead of averaging it away; the uncertainty record for acoustic forcing during cure keeps cure timing separate from acoustic radiation force.

## 7. Experiments that discriminate competing mechanisms

The experimental campaign applies the Table 2 interventions as non-redundant challenges; disagreement between rows is treated as evidence of a missing mechanism. An acceptable record for acoustic forcing during cure must show a replicate test of cure timing without inferring it from a causal contrast between acoustic radiation force and steady streaming; during the causal challenge for acoustic forcing during cure, cure timing is tested against acoustic radiation force. In parallel, a boundary challenge involving bubble interaction probes the boundary condition most likely to change the interpretation, and the resulting uncertainty is carried forward explicitly; the experiment for acoustic forcing during cure separates acoustic radiation force from bubble interaction.

## 8. Model identification and validation for acoustic forcing during cure

Model identification starts from the failure signature paired with Table 2 row one. Transfer is judged on row two, and row three is kept as a structural check on parameter non-uniqueness. [2] [5] [3,4] Decision uncertainty is retained row by row in Table 3 so that one wide confidence interval cannot be masked by the other two. Evidence for acoustic forcing during cure is not accepted from a single nominal condition; within model identification for acoustic forcing during cure, acoustic radiation force is not fitted through bubble interaction. The analysis requires parameter estimation for acoustic radiation force and bubble interaction, follows it with an uncertainty-bounded check on cure timing, and uses prediction against steady streaming as a targeted challenge wherever the two indicate different mechanism or margin; prediction for acoustic forcing during cure keeps bubble interaction independent of steady streaming.

## 9. Qualification envelope and technology decisions

Table 3. Technology-decision matrix for acoustic/vibration response.

| Decision                                                                                  | Minimum evidence                                                                                                                                                                                                                                                                    | Acceptance logic                                                                                                                                                                                                                                                                                              |
|-------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| whether acoustics are a controlled assembly step or an uncontrolled vibration disturbance | The minimum record for whether acoustics are a controlled assembly step or an uncontrolled vibration disturbance is high-speed imaging of bubble and particle motion measured across the relevant state interval with calibration, repeatability and decision uncertainty reported. | The decision is supported if 'sweep frequency through and away from resonance at matched acoustic energy' changes high-speed imaging of bubble and particle motion in the validated direction without activating unintended nodal banding or concentration gradients; otherwise requalification is required.  |
| minimum organisation time before exposure                                                 | Establish minimum organisation time before exposure from repeated hydrophone or calibrated pressure-field mapping measurements on both sides of the intended transfer boundary.                                                                                                     | Acceptance is conditional on a stable hydrophone or calibrated pressure-field mapping response under 'compare standing-wave and traveling-wave configurations' and on the absence of bubble coalescence, translation or collapse damage at the proposed limit.                                                |
| field amplitudes that improve orientation without bubble damage                           | A defensible case for field amplitudes that improve orientation without bubble damage requires state-resolved temperature monitoring during sonication, replicated sufficiently to distinguish systematic change from measurement scatter.                                          | Keep the claim only if 'run acoustics without illumination and illumination without acoustics' does not drive temperature monitoring during sonication outside its demonstrated range and no evidence of loss of alignment because cure begins before the acoustic field reaches steady organisation emerges. |

A separate boundary for steady streaming is the first stress test for acoustic forcing during cure; only after that result is bounded is tested ranges in acoustic radiation force and bubble interaction interpreted; inside the acoustic forcing during cure envelope, bubble interaction and steady streaming define different transfer limits. The record keeps an explicit transfer limit on cure timing outside that inference and reports it as an independent line of evidence; qualification of acoustic forcing during cure bounds steady streaming separately from cure timing.

## 10. Design consequences for acoustic forcing during cure

The usable design window is the intersection of the three Table 3 rows. No single row is permitted to stand in for the others. Engineering action centres on a design change governed by acoustic radiation force; during design implementation for acoustic forcing during cure, steady streaming is constrained by cure timing. In the same test, while minimum organisation time before exposure is controlled independently, an implementation check on steady streaming provides the implementation check and a requalification trigger tied to cure timing marks the stop condition; the acoustic forcing during cure design record separates cure timing from acoustic radiation force. The selected geometry or recipe is therefore tied to evidence for acoustic forcing during cure, not to a single nominal set point; implementation of acoustic forcing during cure treats acoustic radiation force and bubble interaction as different control axes.

## 11. Evidence gaps for acoustic forcing during cure

The acoustic forcing during cure workflow deliberately separates uncertainty in bubble interaction versus steady streaming from scale transfer of acoustic radiation force; this avoids fitting the challenge into the quantity being qualified; for unresolved acoustic forcing during cure transfer, cure timing is studied separately from acoustic radiation force. Independent replication of cure timing is then examined on its own terms before any transfer statement is retained; the evidence gap in acoustic forcing during cure distinguishes acoustic radiation force from bubble interaction.

## 12. Qualification outcome for acoustic forcing during cure

A defensible release requires independent evidence for every Table 3 row. Failure of any one row reopens qualification. For acoustic forcing during cure, the evidence chain starts with agreement between measurement and prediction for acoustic radiation force; at final qualification of acoustic forcing during cure, acoustic radiation force is reconciled with bubble interaction. It then adds causal evidence that separates bubble interaction from steady streaming, while a renewed-evidence trigger when cure timing changes is retained as a separate control so the three sources of information cannot compensate silently; the closing acoustic forcing during cure claim keeps bubble interaction distinct from steady streaming.

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**Competing interests**

The author is Founder, CEO and CTO of 3Dresyns by Resyner Technologies S.L. No comparative product recommendation is made.

**Data availability**

No new experimental dataset was generated for this review.