High Power Ultrasonics

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Overview

• Ultrasonics
• Generation
• Effects
• Applications
• > 20 kHz
• Most familiar application (1.6 to 10 MHz-GHz)
C-scan

Listen for echoes and scan in 2-D
Total of 3-D image
• Most familiar application (50 to 100 kHz)
• Most familiar application (bats 14 to 150 kHz)
• Stone, tissue destruction (1 to 20 W)

Images from Wikipedia
Waves
Longitudinal waves

Compressional waves

Speed of sound in air and water are 343 m/s and 1484 m/s

\[ c = \sqrt{\left( \frac{E}{\rho} \right) } \]

Equipment
Ultrasonic equipment

- Power Supply
- Control Level
- Actuator/Stand
- Converter
- Booster
- Horn
- Fixture
Ultrasonic power supply

• Controller (Modular design)
  – Human interface
  – I/O, PLC
  – SPC/Data ACQ.

• Power module
  – Line conversion
  – Tuning
  – O/L Protection

Graphics: Branson Ultrasonics
Standard system

- Modular design
- Remote power supply
- Remote controls
- Easy for system integration
Ultrasonic power supplies

• All suppliers offer various control levels:
  – Basic for PLC control
  – Time
  – Distance, Time, Power, Etc

• Application dependent

Graphics: Branson Ultrasonics
Actuator

• Applies welding force
• Pressure regulator
  – Maximum force
• Flow control
  – Down speed
  – Force buildup
• Stack mounting
• Encoder
Stack

• Three major components:

Converter (Linear motor)  Booster  Horn/sonotrode

Graphics: Branson Ultrasonics
Stack and resonance

- All parts are tuned to one frequency
- The system operators at resonance
Stack vibrations

• Axial is the ideal mode for ultrasonic welding

• All component are design as resonators

• All other modes tend to:
  – Reduce efficiency
  – Promote failure

Graphics: Branson Ultrasonics
Converters
Converter/Transducer

- Heart of the system
- Converters electrical energy to mechanical
- Motor
- 90 to 97% efficient
- Most are piezo-electric
Converter

• Most are piezo-electric
  – High voltage (1-5 KV)
  – Ceramic crystals
  – $(\frac{1}{2} \lambda)$

• Less popular are magnetostrictive
Stack output

Amplitude (P-P)
Typical converter output

- Peak to Peak amplitude
- At 100% output:

- 15 kHz: 30 microns
- 20 kHz: 20 microns
- 30 kHz: 15 microns
- 40 kHz: 10 microns
Converter characteristics

• Maximum power
• Frequency
• Efficiency
• Cooling
  – Forced air
  – Static Air
Converter failures

• Off modes of vibration/wrong frequency
  – Usually in the horn

• Impact
  – Jack hammering
  – Contact with fixture

• Cooling
  – No air
  – Poor design
Boosters & Horns
Boosters

- Mechanical amplifier
- Discreet factors
- Materials:
  - Al: Cost effective
  - Ti: Tough applications
- Mounting point of stack

Graphics: Branson Ultrasonics
Booster/horn gain

- Ratio of volume above and below nodal plane

\[ F = ma \]

From equilibrium:

\[ F_1 = F_2 \Rightarrow m_1 a_1 = m_2 a_2 \]

\[ \frac{m_1}{m_2} = \frac{a_2}{a_1} = Gain \]

Measure volume using liquid displacement method
Horns/Sonotrodes

• Applies:
  – Ultrasonic energy
  – Force

• Tuned (½ and full $\lambda$)

• Material
  – Al: Cost effective
  – Ti: High gain
  – Steel: High wear
  – Ferro-Tec
  – Coated: High wear
Horns (Half and full $\lambda$)

- Application dependent
- Allows welding internal to the application

Graphics: Branson Ultrasonics

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Horns (Full $\lambda$)

- Application dependent
- Allows welding internal to the application

Graphics: Branson Ultrasonics

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Horns-replacement tips

• Cost effective solution with high wear application:
  – Inserts
  – Glass filled staking

• Can be re-machined
Horn design

• Three typical horns
Step horn

- Early design
- Moderate amplitude
- High stress
- Easy to manufacture
Exponential horn

- Moderate stress
- High amplitude

Graphics: Branson Ultrasonics
Catenoidal horn

- Low stress
- High amplitude
Stack amplitude:

20 μm<sub>pp</sub>  1:2.5 (50 μm<sub>pp</sub>)  1:2.0 (100 μm<sub>pp</sub>)

20 μm<sub>pp</sub>  1:1.0 (20 μm<sub>pp</sub>)  1:3.0 (60 μm<sub>pp</sub>)

Graphics: Branson Ultrasonics

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• Mounting

Booster

Motion

Clamp ring

Nodal plane

Rubber O-Rings

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Booster

• Deflection – asymmetrical loading
Booster

• Rigid Mount booster (converter)
~900 VAC @ 20 kHz (0-5 Amps) Tuning via zero phase between V and I

PZT converter
Produces 20 microns p-p vibrations

Mechanical booster

“Horn”-delivers mechanical Vibrations to parts (20-120 p-p amplitude)
Axial mode of vibration

Ideal mode vibration
Uniform and in phase

Horn face that contacts part
Flexural mode of vibration

Possible flexural mode
Ultrasonic frequencies

- Typical 20 and 40 kHz
- The higher the frequency the smaller the converter & stack
- Power is limited by converter capacity
- The power output is limited to size due to heat generation
Ultrasonic frequencies

- Manufacturers rate converters by different duty cycles
- There is always some controversy on maximum power
- Typical max. power for a single converter (value vary for manufacturer):

![Graph showing the relationship between operating frequency (kHz) and maximum continuous converter power (W).](image)
Liquid processing

Cavitations

Cavitation and Implosion

- Cavitation bubble growth in negative pressure
- Maximum Bubble Size
- Bubbles collapse in compression
- Cycle repeats: New bubble growth
Cavitation
Acoustic Cavitation

Multi-Bubble Sonoluminescence:

1 cm Ti horn

50 μm
Multibubble Cavitation:

Hot Spot Conditions in Bubble Clouds

Temperature: 5000 K

Pressure: ~300 atm

Duration: ~1 nsec

Cooling rate: > $10^{12}$ K/sec

Nucleation

• Without nucleation the cavitations process will not start without extremely high pressures

• The nucleation process acts a stress concentration point to cause tensile failure of the liquid (water =100 atms)

• Edges, dusts, etc

• Growth occurs when the local pressure ($p$) is less than the vapor pressure ($p_v$)
Nucleation

• Most often at:
  – Edge
  – Dust
  – Can be induced
    • Laser

Dirt with rough edges

Liquid

Liquid can not flow into voids because of surface energy
Growth

• Cyclic growth
  – At high pressure the bubble decreases in size
  – At low (negative) pressure the bubble grows
  – The overall growth is positive
Rectified diffusion

- Once a bubble forms, the pressure change:
  - During compression the liquid near the bubble has increased saturation limit
    - Gas diffuses from the bubble into the liquid
    - The surface area is small because of compression
  - During rarefaction the liquid becomes super saturated
    - Gas diffuses from the liquid into the bubble
    - The surface area is large
  - The relative change in surface area causes more gas into the bubble overtime
Collapse

• This is similar to buckling issues
  – Blowing a bubble that is too large
  – Soap bubble too large
Collapse

• Isothermal
  – High surface area to volume ratio
  – As bubble collapses the gas in compressed
  – Not until the very last moment does the temperature climb
  – 5000 K
Collapse

Asymmetrical collapse

- Near by forces
  - Particle
  - Bubbles
  - Temperature
  - Pressure
  - etc

Jetting
Collapse

Storz doulih shock wave : web image for Ultrasonic shock wave therapy equipment.  
(http://www.lockstockuae.com/products/_storz_duolith_shockwave) visited on  
5/13/2011
Propagation
Propagation
Far field vs near field
Far field vs near field

Near field

Far field

Source

$r=a$

Planar wave

Diffraction patterns

Edge effect waves

$R = \frac{\pi a^2}{\lambda}$
Continues treatment
Continues treatment
Applications

• **Industrial**
  – Metal welding
  – Plastics welding
  – Cutting
  – Drilling

• **Bio**
  – Biofuels
  – Medical
Model assumptions:
1. No losses on motion with the sample
2. The lower part remains perfectly stationary
3. Constant material properties
4. Constant displacement and forces
5. No inertial effects
6. No stored energy
Frictional heating

- Power –defined as:
  \[ P = F \cdot v \] 
  - frictional force; \( v \) –velocity

- Instantaneous velocity –defined as:
  \[ v(t) = A_0 \omega \sin(\omega t) \]

- Instantaneous displacement –defined as:
  \[ x(t) = -A_0 \cos(\omega t) \] 
  - \( A_0 \) – peak displacement
Frictional heating

• Instantaneous dissipated power –defined as:

\[ P(t) = F \cdot A_0 \omega \sin(\omega t) \]

• Frictional force –defined as:

\[ F = \mu \cdot f_f \] –applied normal force

• Instantaneous power –redefined as:

\[ P(t) = f_f \mu A_0 \omega \sin(\omega t) \]
Frictional heating

- The average Power —estimated by integrating the previous function over a wave period —defined as:

\[ P_{avg} = \frac{2f\mu A_0 \omega}{\pi} \]
Frictional heat

Additional assumptions:
- Amplitude at the weld interface - approximately 50% of the prescribed amplitude
- 1-D heat flow (only concerned about peak temp)
Heating

- To estimate bond line temperature – a semi infinite one dimensional model – assumed

\[
\theta(x, t) = \theta_i + \frac{2 \cdot \dot{q}_0}{\lambda} \left[ \sqrt{\frac{\kappa \cdot t}{\pi}} \cdot \exp\left(-\frac{x^2}{4 \cdot \kappa \cdot t}\right) - \frac{x}{2} \cdot \text{erfc}\left(\frac{x}{2\sqrt{\kappa \cdot t}}\right) \right]
\]

- \(\theta\) – temperature,
- \(x\) – position,
- \(t\) – time,
- \(\theta_i\) – initial temperature of the solid,
- \(\dot{q}_0\) – heat flux at the surface,
- \(\lambda\) – thermal conductivity,
- \(\kappa\) – thermal diffusivity \((\lambda/\rho C)\),
- \(\text{erfc}\) \((z)\) – complementary error function
Heating

• Consider only the final size of the weld
• Estimate the weld failure area
• Estimate the heat flux at the surface (x=0)

\[ q_0 = \frac{P}{2A} \]

\[ A = \pi r^2 \]
Frictional heating

![Graph showing frictions heating over time and power.](image)
Heating during metal welding

Contours of Temperature
- min = 295, at node # 220418
- max = 295, at node # 220418
- max displacement factor = 100
Metal welding resonance
Metal welding continuous
Cutting
Food cutting

Dukane Ultrasonics
Food packaging - Cheese
Food packaging-liquid
Dukane Ultrasonics
Cutting composites
Cookie Dough
Cheese cutting
Candy bar
Humidifier
De-foaling
Plastic welding
Background

• Heating
• Joint design acts as stress concentrator
• **Energy director**, shear joints, etc.

\[ Q = \frac{E'' \omega \varepsilon_0^2}{2} \]
Background

• Molecular friction
Background

• Heating
• Motion is a sinusoidal function
  – \( \varepsilon \): strain amplitude
  – \( \omega \): Frequency

\[
\varepsilon = \varepsilon_0 \cos(\omega t)
\]
\[
\sigma = E\varepsilon
\]
Background

• Thus average heating:

\[ Q = \frac{E'' \omega \varepsilon_0^2}{2} \]

– Temperature:
  • Frequency (\( \omega \)) Constant
  • Amplitude (\( \varepsilon \)) Key parameter
  • \( E'' \)-Loss modulus is difficult to define

– Controlling the amplitude allows temperature control!

– The wrong temperature, dinner is ruined!!
Background

Melt viscosity of plastics:

\[ \eta = A \, e^{\frac{E}{RT}} \]
Background

Melt viscosity of plastics:
Melt viscosity of plastics:

\[ Q = \frac{E'' \omega \varepsilon_0^2}{2} \]

\[ T \approx \varepsilon \]

\[ \eta = A e^{E/RT} \]

\[ \eta \approx 1/\text{Amplitude} \]
Melt viscosity of plastics:

Bridging

No Bridging

T1 > T2

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• With collapse constant:

![Graph showing relationship between bondline thickness and amplitude](image-url)
• Typical cross sections:

High Amplitude
Thin Bond Line

Low Amplitude
Thick Bond Line
• Amplitude and weld strength:
- Amplitude profiling

![Graph showing different types of amplitude profiling: Conventional Amplitude, Ramped Amplitude, Stepped Amplitude, and the time when amplitude is changed.](image)
Amplitude profiling

- $P = V \times I$
- Current is limited by wire size
Tooth paste tubes

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Blister pack

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Other industrial application

- Rock cutting
- Additive manufacturing
- Particle removal
- etc
Chemical processing

• Biofuels
  – Enhance biodiesel (60 min to 15 s)
  – Enhance ethanol (No jet cooking)
  – Ionic liquids
  – etc
Biodiesel

Soy Beans Diesel Fuel
Modeling of liquid processing
Modeling of liquid processing
Water treatment
Medical

• Drug delivery
• Cutting
• Adhesive removal
• Stone breaking
• etc
Plaque removal
Plaque removal
Thanks!!

• CIRAS
• UIA
• Questions
• Comments