UNIVERSITY of GLASGOW

Experimental and computational modelling of vibration performance of ultrasonic tools for manufacturing applications

UIA Symposium, 2002

Dr Margaret Lucas and Andrea Cardoni

Department of Mechanical Engineering, University of Glasgow

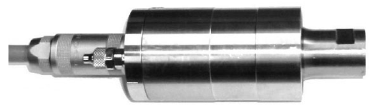
UNIVERSITY of GLASGOW

Objectives

- Study the causes of component failure in simple and complex ultrasonic cutting systems by finite element (FE) modelling.
- Investigate geometric modifications of the ultrasonic components in order to reduce stress.
- Characterise the vibration behaviour of ultrasonic components by FE and modal analysis.
- Propose geometric modifications to improve vibration performance.
- Characterise the nonlinear responses of ultrasonic systems.
- Illustrate the theory of Nonlinear Cancellation Coupling.
- Propose strategies to reduce effects of nonlinear behaviour and to reduce nonlinearities.

Ultrasonic Systems and Components

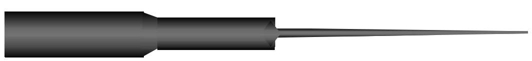
System exciter



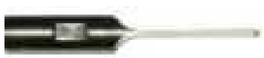
Piezoelectric transducer

Customised Ultrasonic Horns

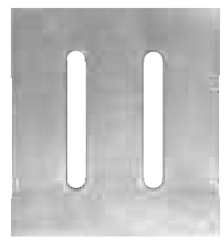
One and a half wavelength Bar horn



One wavelength blade

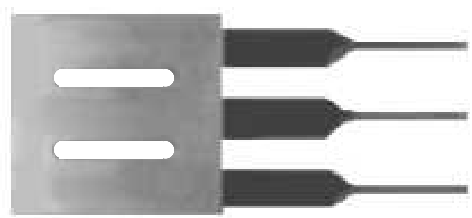


Half wavelength blade



Double-slotted block horn

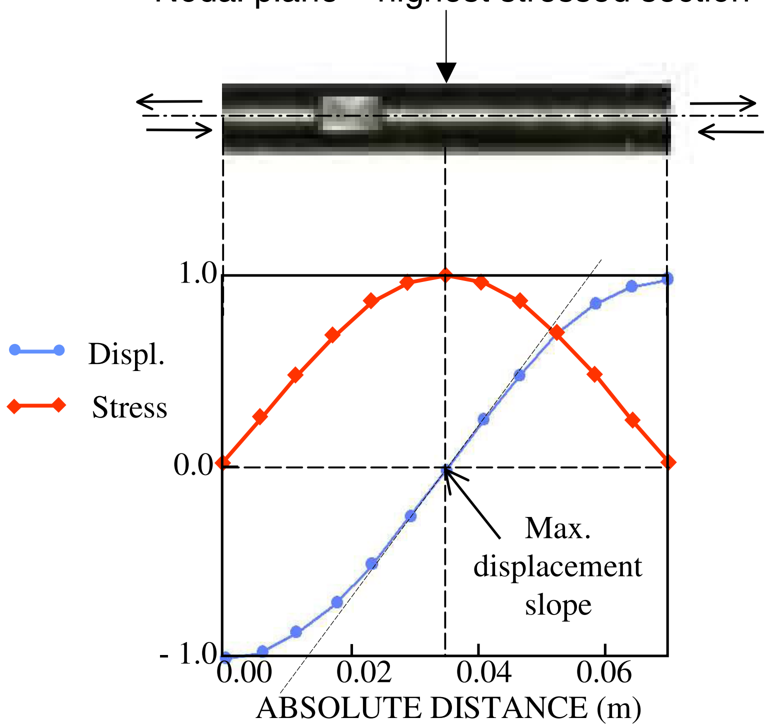
Single-slotted block horn



Three-bladed cutting head

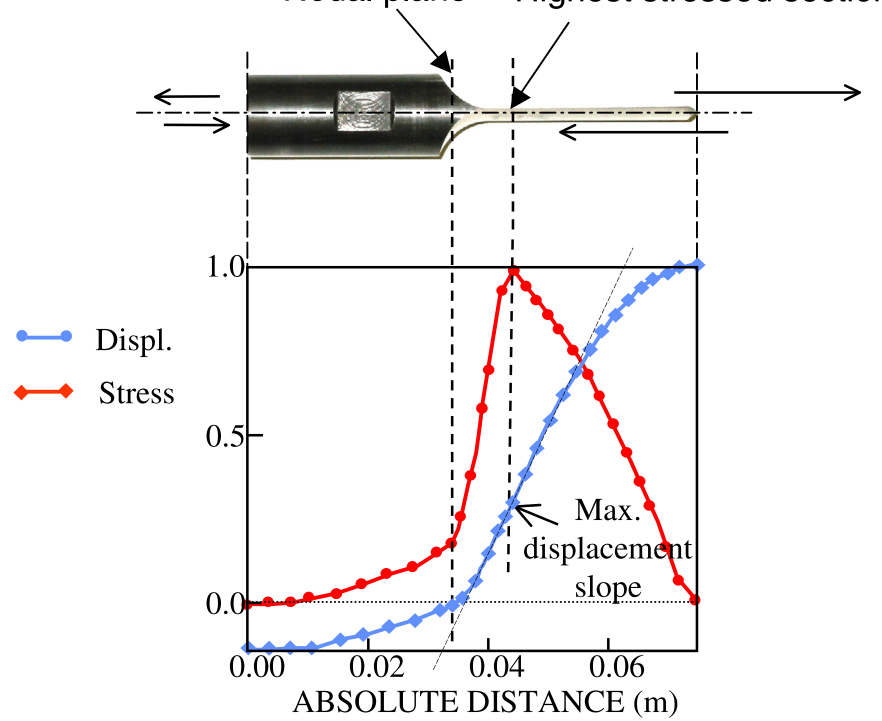
Normalised Stress and Displacement

Bar Horn of Constant Section



- In a cylindrical horn the longitudinal node corresponds to the highest stressed section.
- The maximum displacement slope coincides with the highest stressed section of the horn.

High Gain Blade

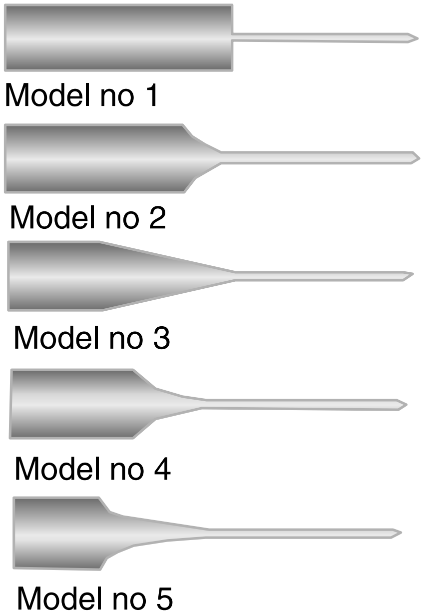


- The highest stress occurs at the steep section reduction.
- If the node is close to the highest stress section, the maximum stress is greater.

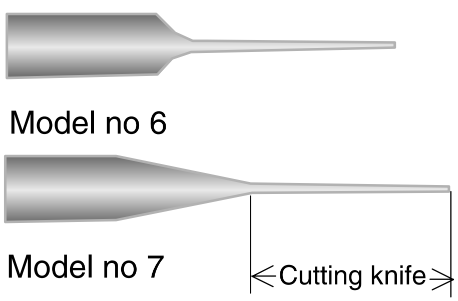
UNIVERSITY of GLASGOW

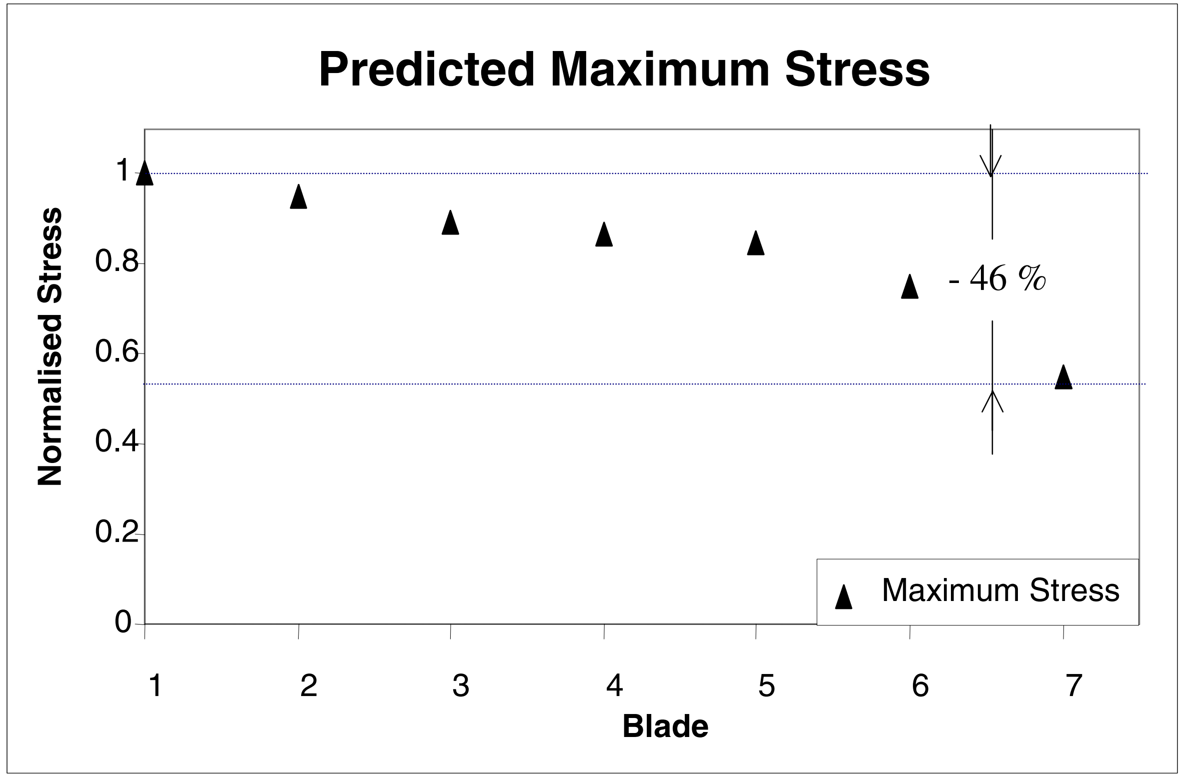
Reducing Maximum Stress by using Alternative Blade Geometries

Step Redesign



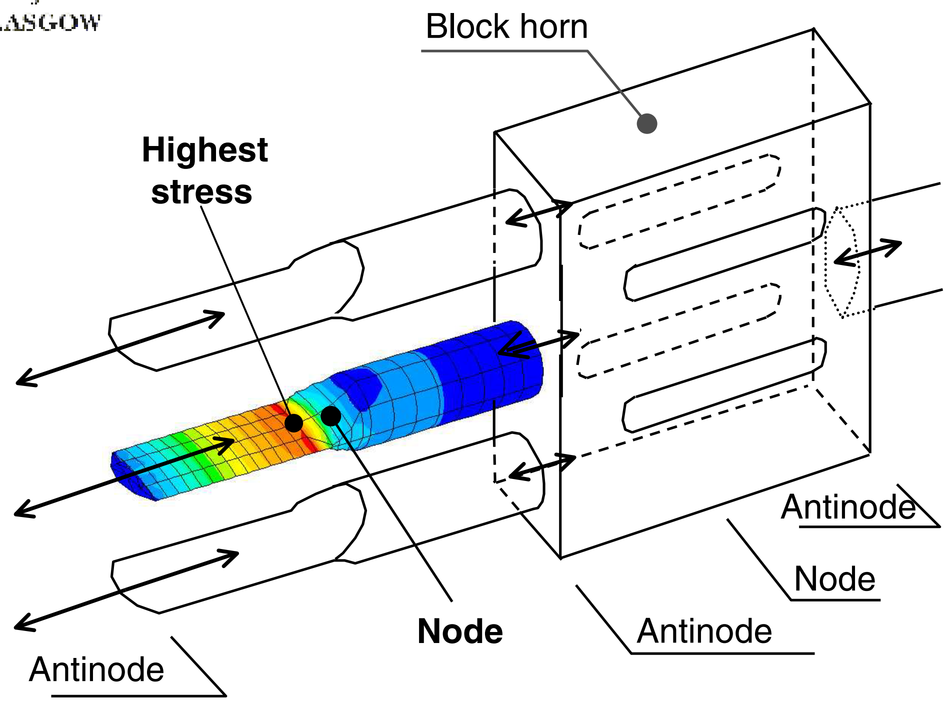
Tapered cutting knife

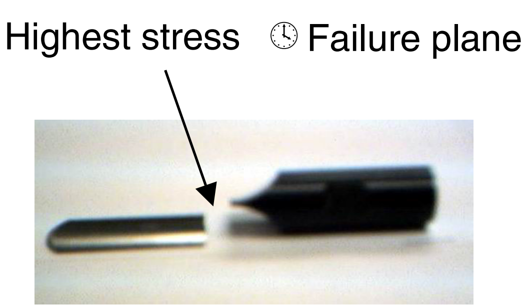




- Redesign of blade step profile reduces stress.
- In particular, tapering the cutting knife provides significant stress reduction.

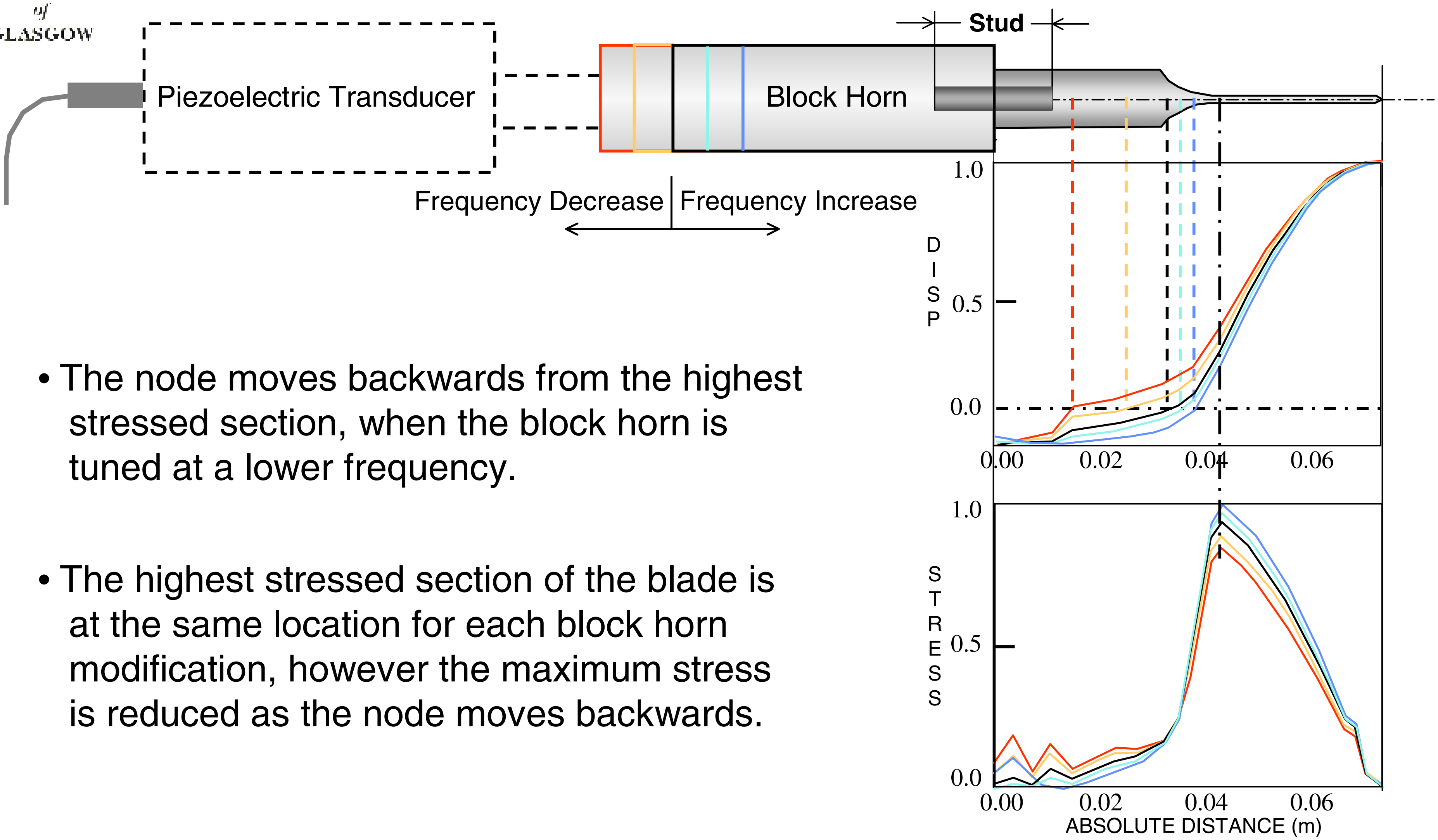
Stress Distribution in the Central Blade of a Cutting Head





- Block horn and blades are tuned at the same frequency (35 kHz).
- The highest stress occurs after the blade step.
- Blade node and highest stressed section are very close.
- Investigate the effect of shifting the blade node backwards into the thicker blade section to reduce stress at the failure location.

Shifting the Node by System Detuning

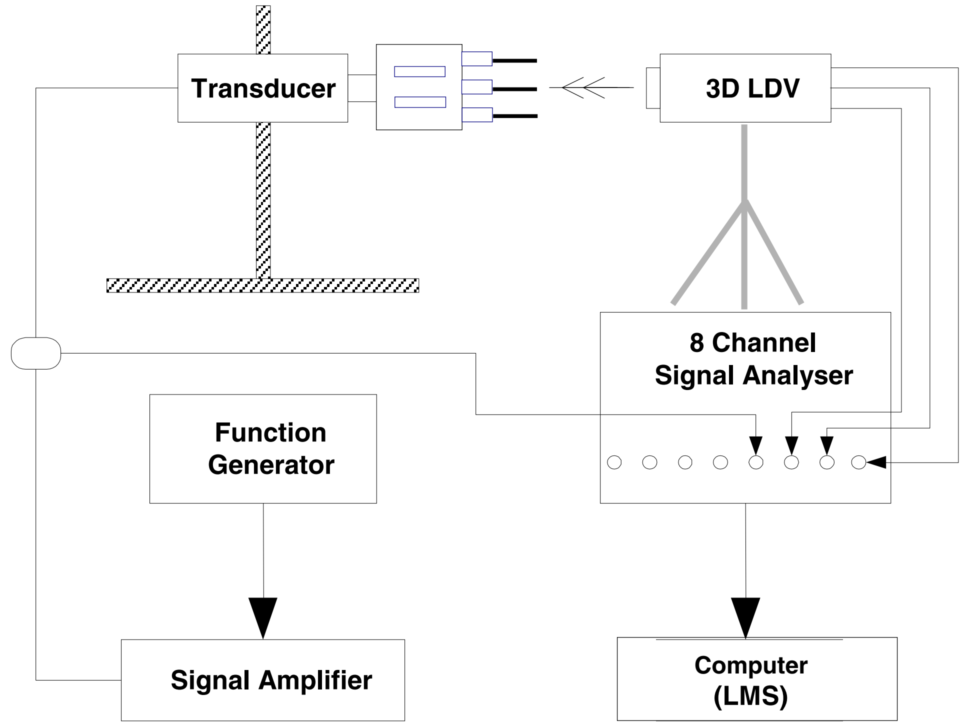


- The node moves backwards from the highest stressed section, when the block horn is tuned at a lower frequency.

- The highest stressed section of the blade is at the same location for each block horn modification, however the maximum stress is reduced as the node moves backwards.

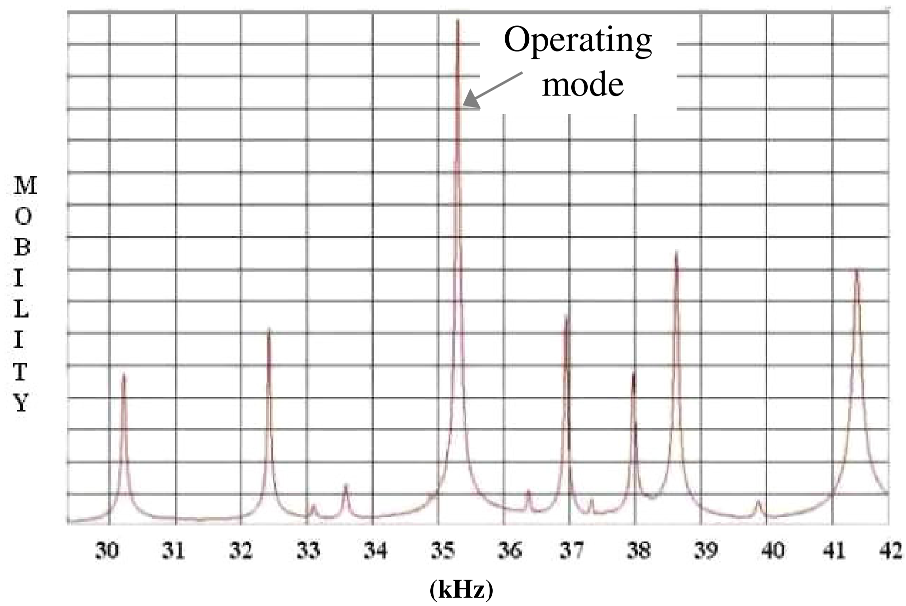
Experimental Modal Analysis

- Modal analysis characterises a structure in terms of its natural frequencies, damping values and mode shapes.
- A 3D laser Doppler vibrometer (LDV), signal analyser and modal analysis software (LMS) allows the modal parameters to be extracted.
- Modal analysis can be used in conjunction with FE models to improve model predictions and assist in redesign.
- The experimental set-up can be used to measure frequency response functions (FRFs) or characterise the nonlinear response.

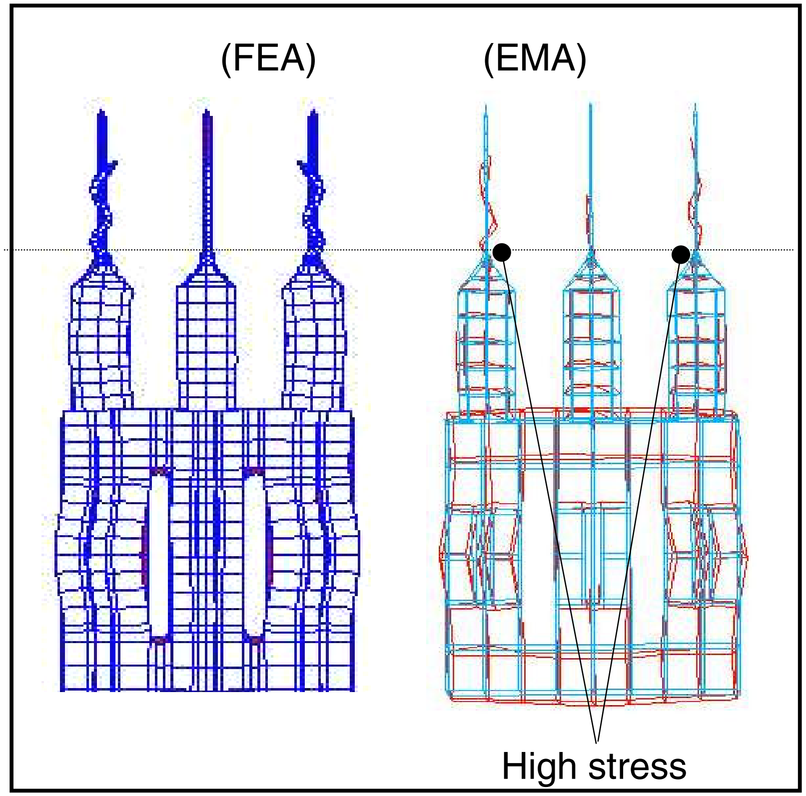


Modal analysis using a 3D LDV

Frequency Response Functions and Modal Properties



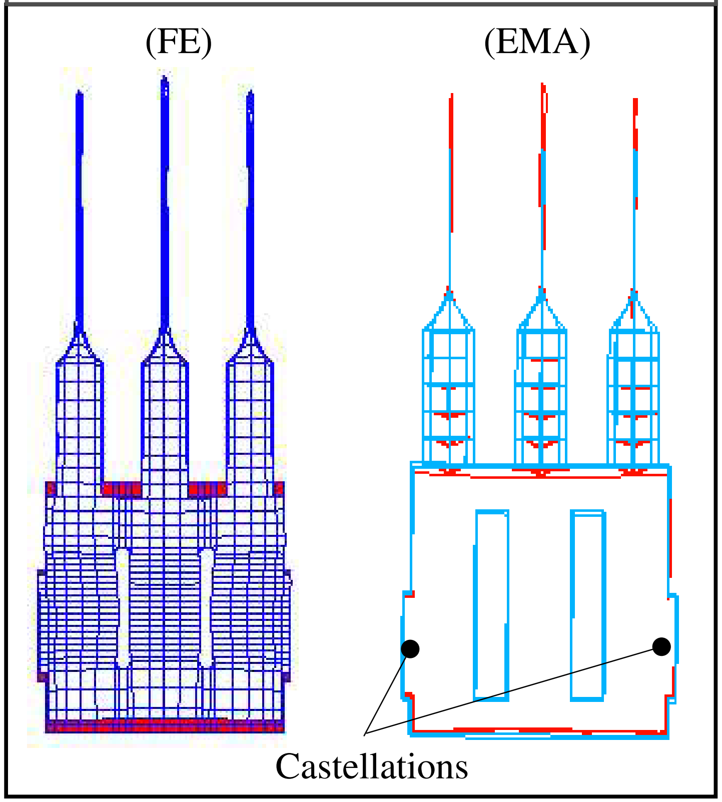
- The FRF illustrates the modal density around the operating frequency of a three bladed cutting head.



- The central blade vibrates in a pure longitudinal mode, but the outer blades are characterised by longitudinal and flexural responses.
- Participation of flexural responses in the operating mode increases the stress in the outer blades.
- Block horn design must focus on constraining fexural responses.

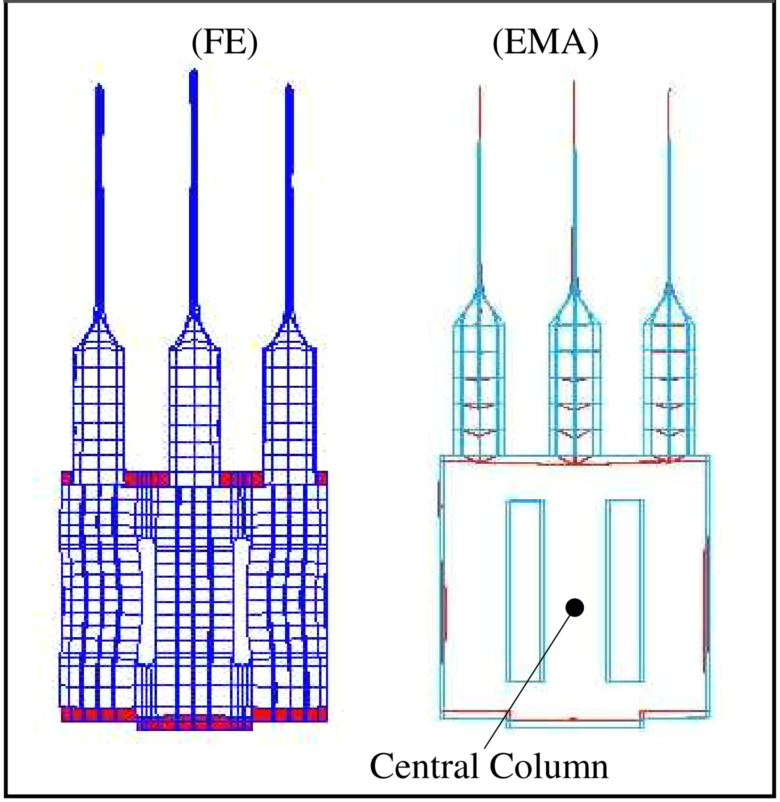
Block Horn Redesign Strategies

Block with castellated outer columns



Castellating the outer columns restricts flexural motion of the outer blades in the longitudinal mode.

Block horn with longer central column



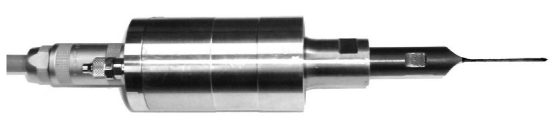
A longer central column also removes flexural responses in the longitudinal mode.

Nonlinear Effects

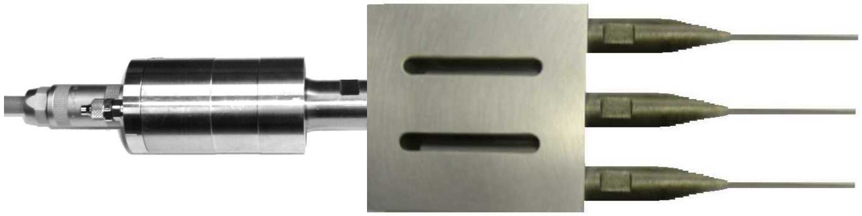
Modal interactions in nonlinear systems can arise when the system is harmonically excited in the vicinity of a natural frequency. In particular, if special relationships (combination resonances) between two or more linear modes and the excitation frequency exist, the system response contributes more modes. Effects of combination resonances are high noise level, component fatigue and poor operating performance.

Underneath are two ultrasonic cutting systems which are prone to these effects due to nonlinear behaviour.

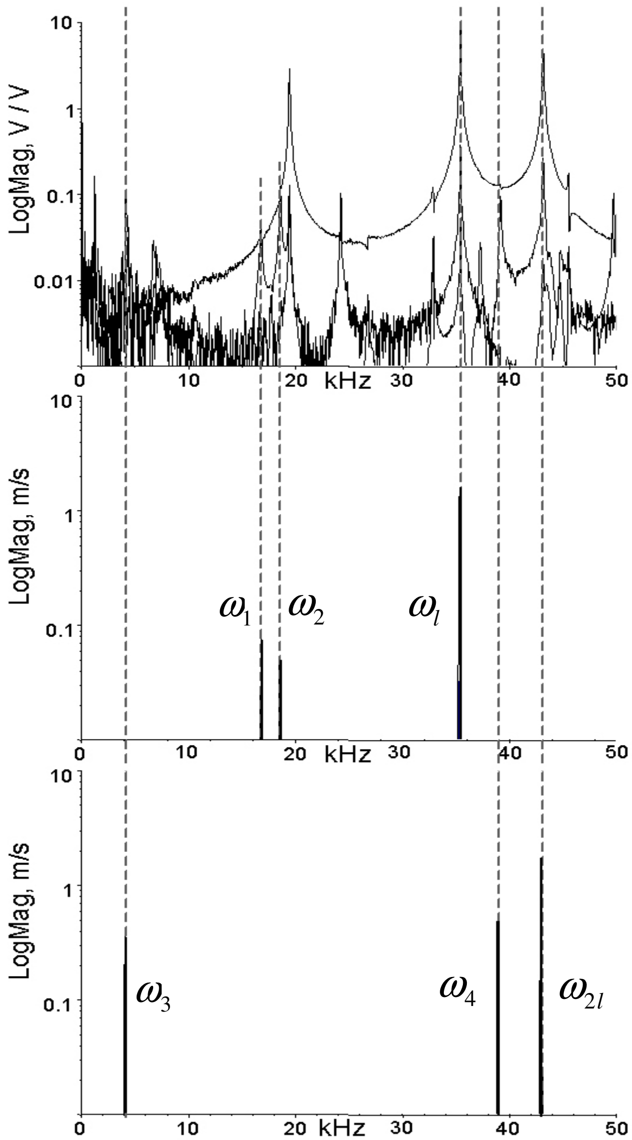
Single-Blade Cutting System



Three-Blade Cutting System

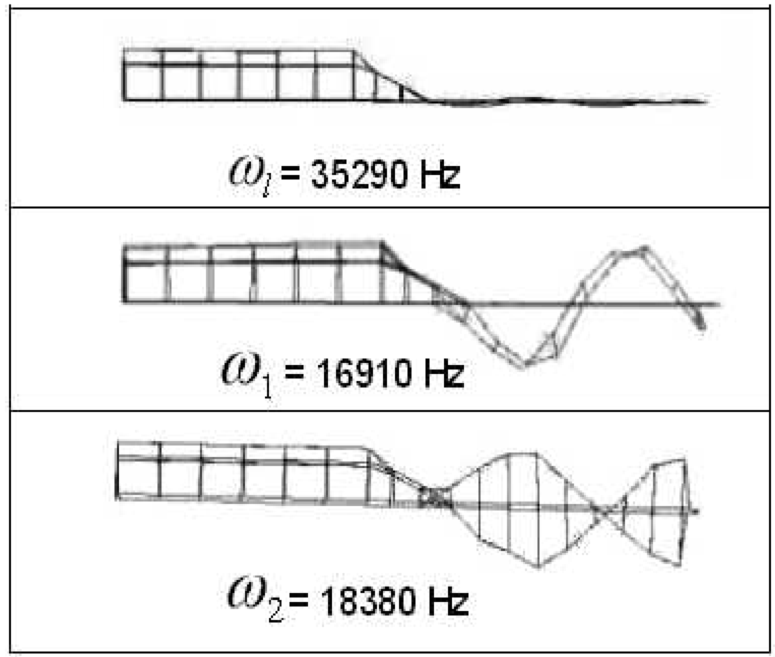


Combination Resonances in a Single-Blade Cutting System



- **System driven at 35.29 kHz**

  Combination I: $\omega_l \approx \omega_1 + \omega_2$

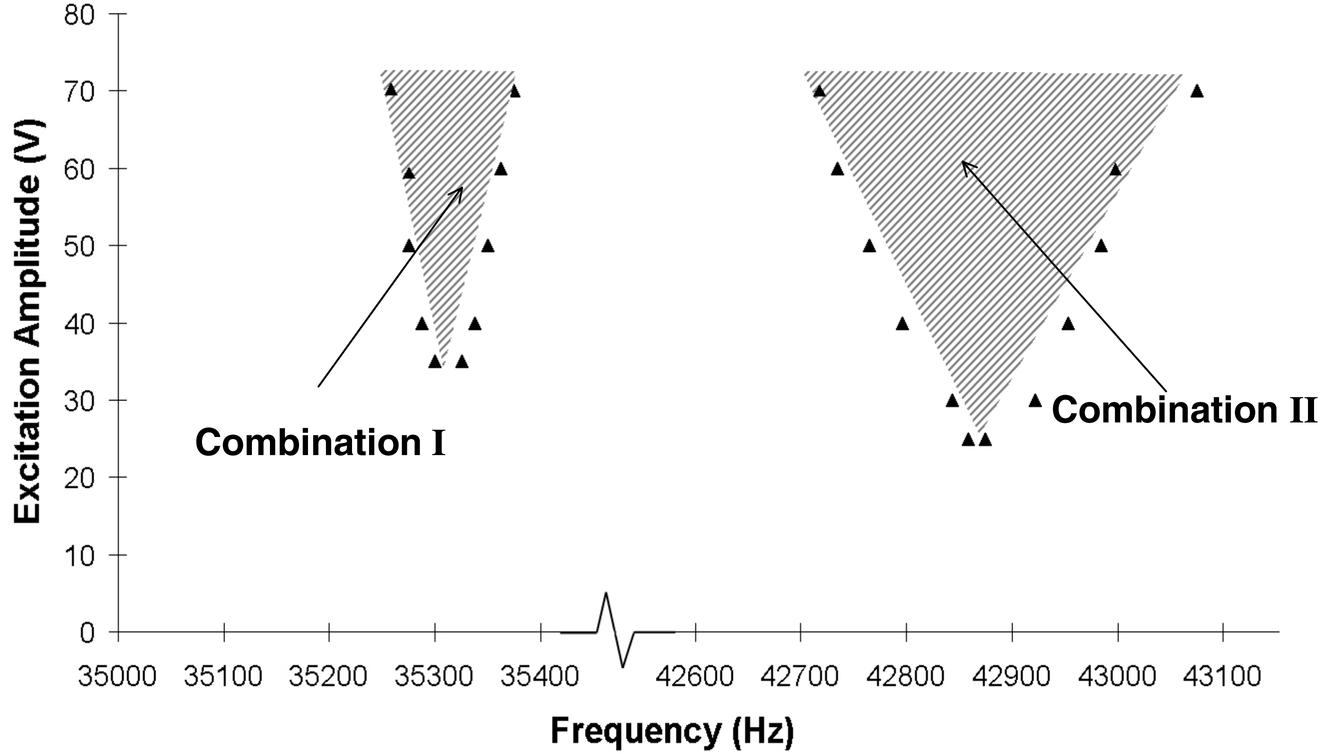


Measured blade mode shapes

- **System driven at 43.1 kHz**

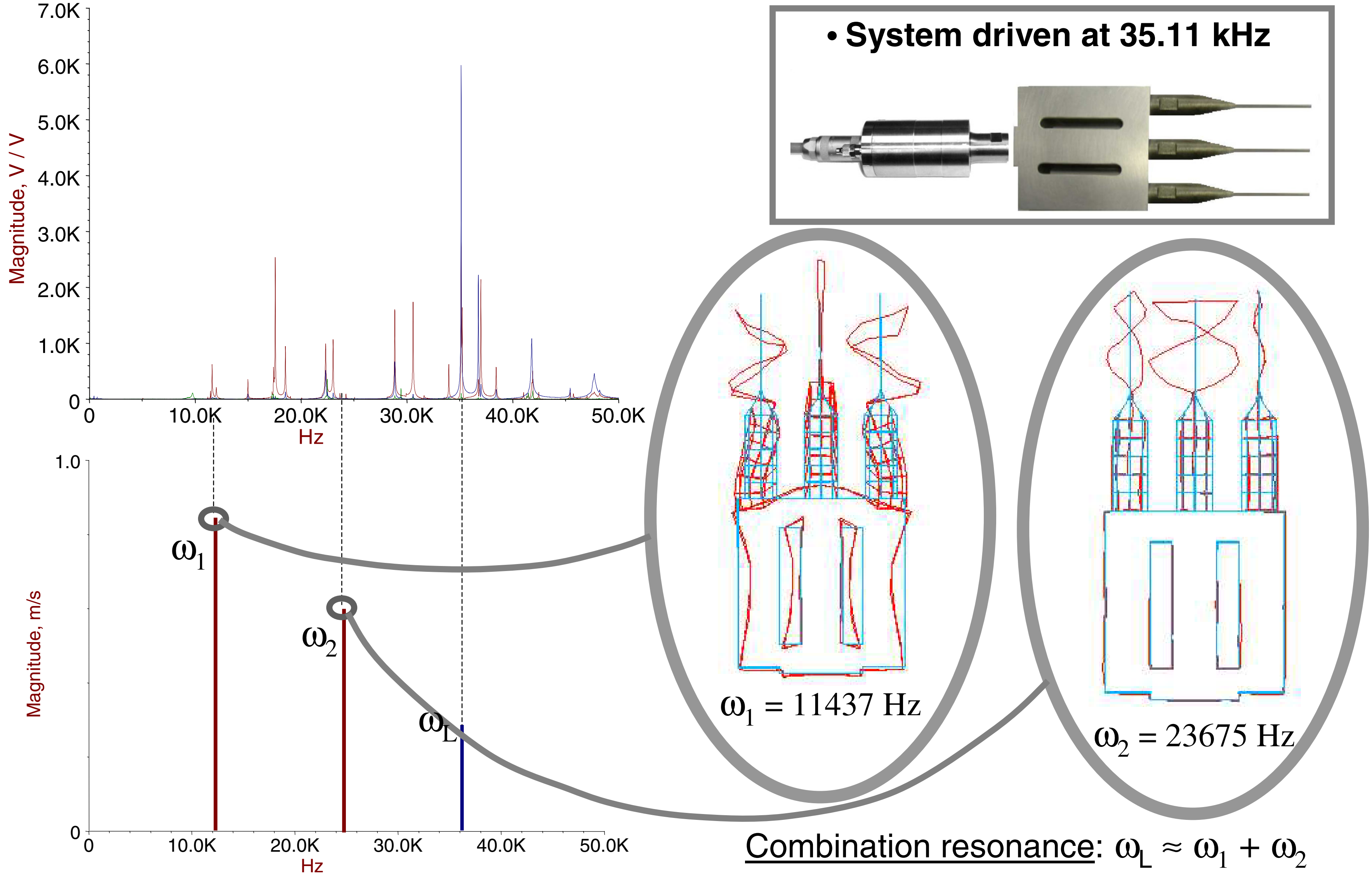
  Combination II: $\omega_{2l} \approx \omega_3 + \omega_4$

Stability Regions



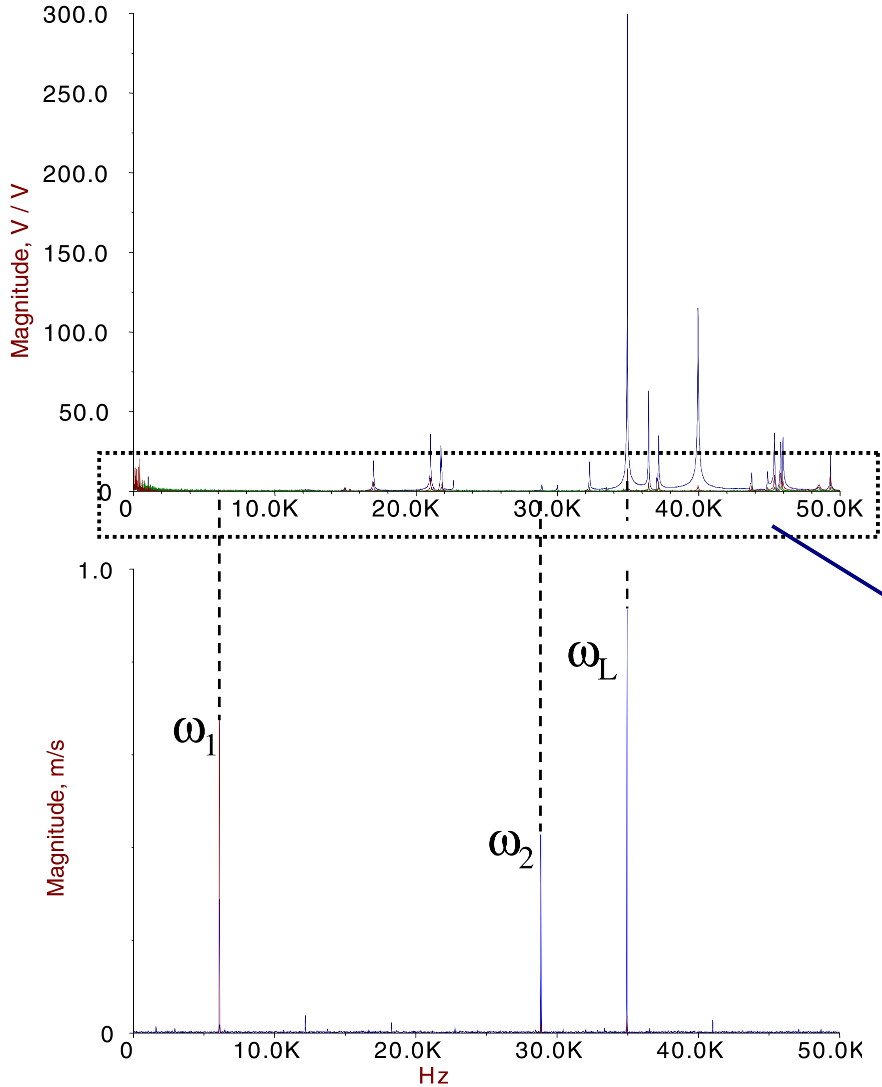
For the single blade system, mode combination II has a lower threshold and wider unstable region

Combination Resonances in Three-Blade Cutting System I



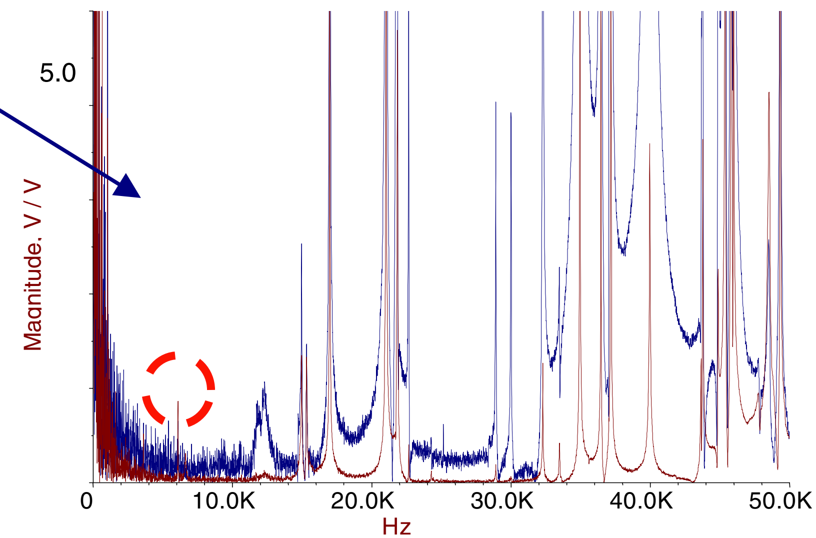
Combination resonance: $\omega_L \approx \omega_1 + \omega_2$

Combination Resonances in Three-Blade Cutting System II



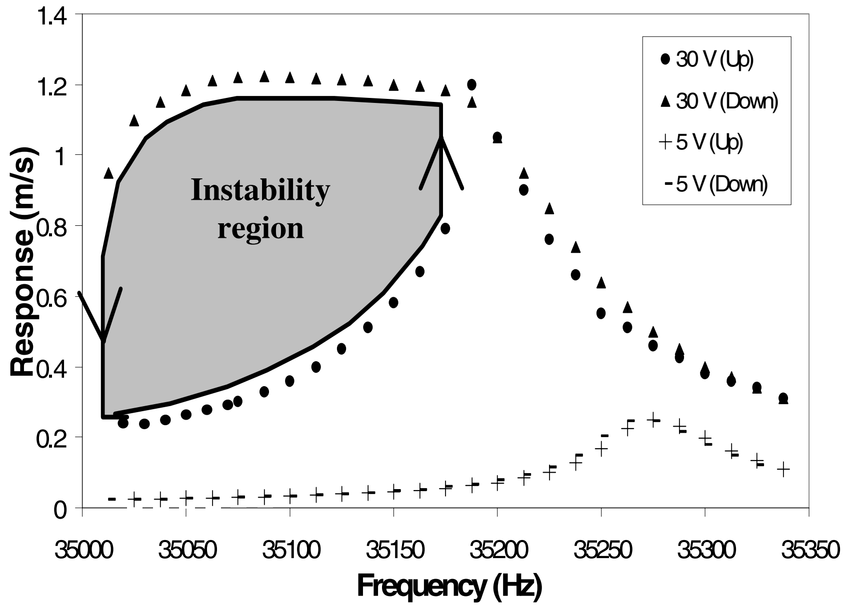
- **System driven at 34.945 kHz**

A single-slotted horn cleans the response spectrum



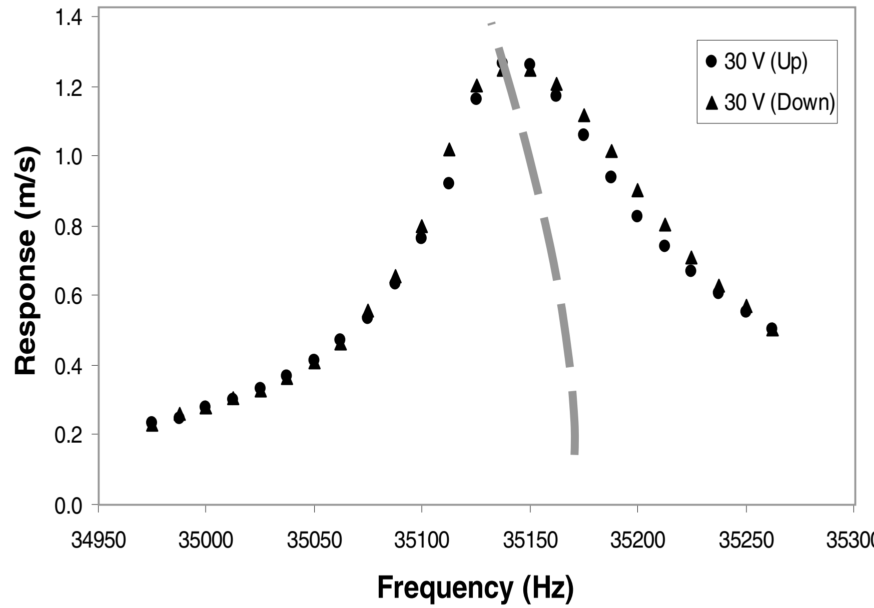
Thermal Effect on the Transducer Characteristic

Frequency sweep carried out on cold transducer



The transducer shows a clear softening characteristic highlighted by the jump phenomenon and a wide unstable region

Frequency sweep carried out on hot transducer

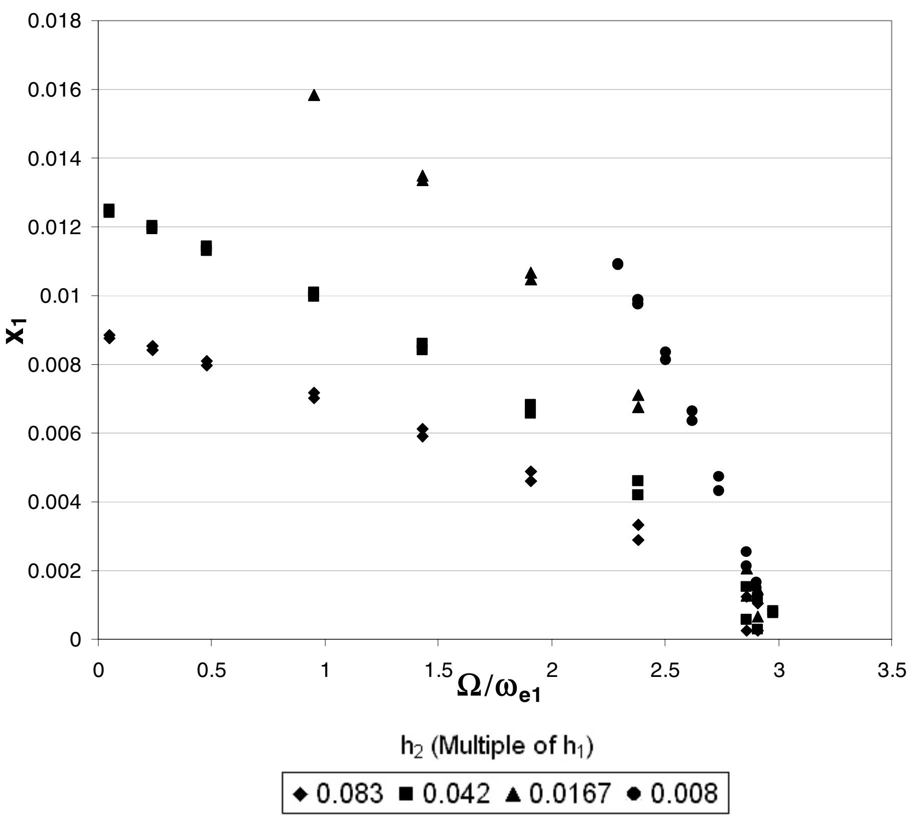


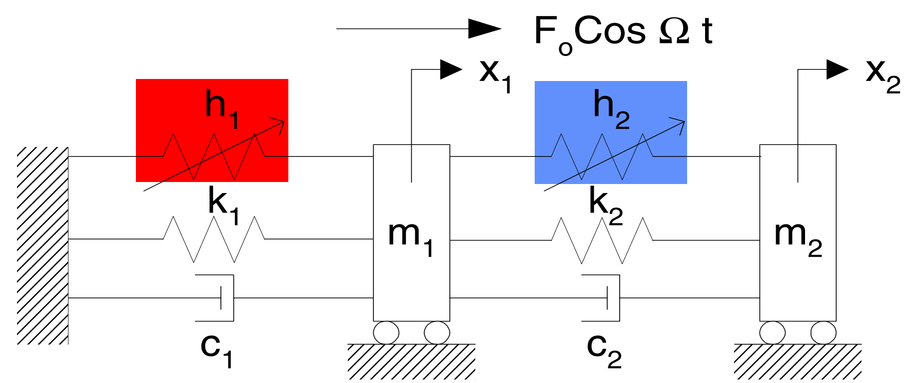
The transducer still shows a softening characteristic, but no jump phenomenon or unstable region

Nonlinear Cancellation Coupling Analytical Theory

UNIVERSITY of GLASGOW

Nonlinear response





Equations of Motion

Hardening cubic stiffness

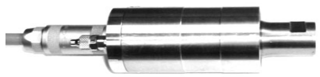
$$m_1\ddot{x}_1+(c_1+c_2)\dot{x}_1-c_2\dot{x}_2+(k_1+k_2)x_1-k_2x_2+h_1(x_1)^3+h_2(x_2-x_1)^3=F_o Cos\,\Omega t$$

$$m_2\ddot{x}_2+c_2\dot{x}_2-c_2\dot{x}_1+k_2x_2-k_2x_1-h_2(x_2-x_1)^3=0$$

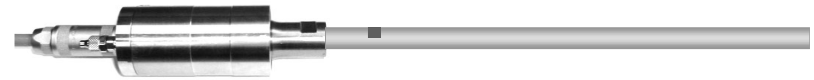
Softening cubic stiffness

UNIVERSITY of GLASGOW

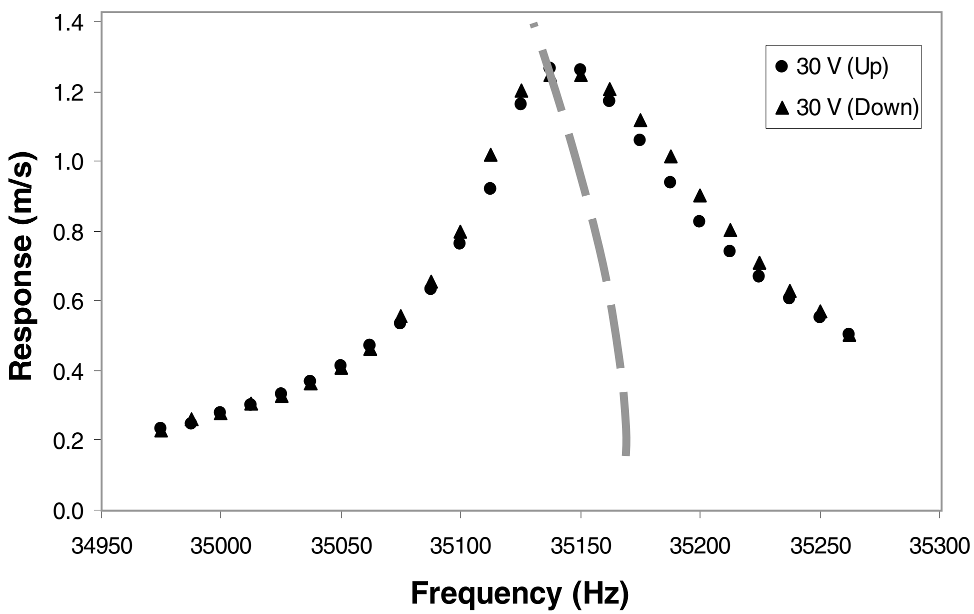
Effect of Tuned Bar on Response Characteristic (Case I: Excitation 30 V)



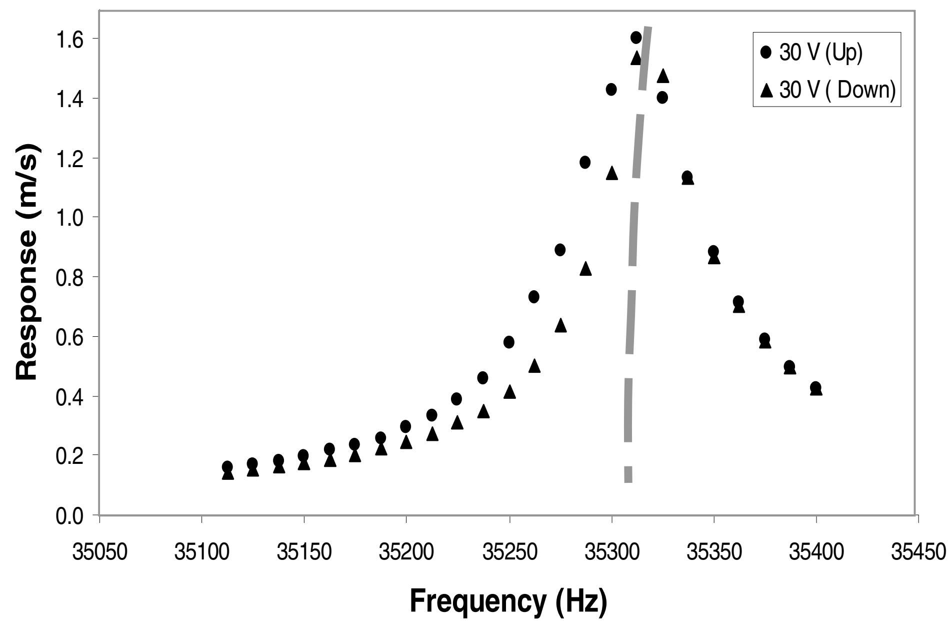
Transducer



Transducer and 1.5 wavelength bar horn system



The transducer exhibits a softening characteristic

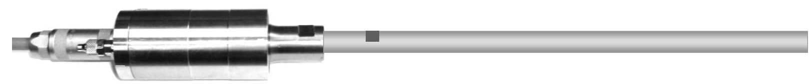


The transducer-bar horn system exhibits a slightly hardening characteristic

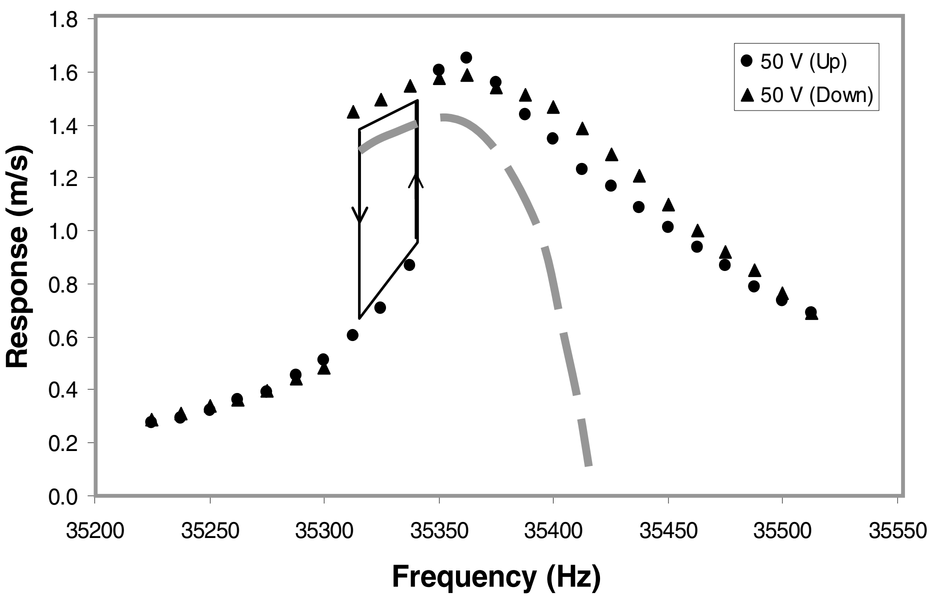
UNIVERSITY of GLASGOW

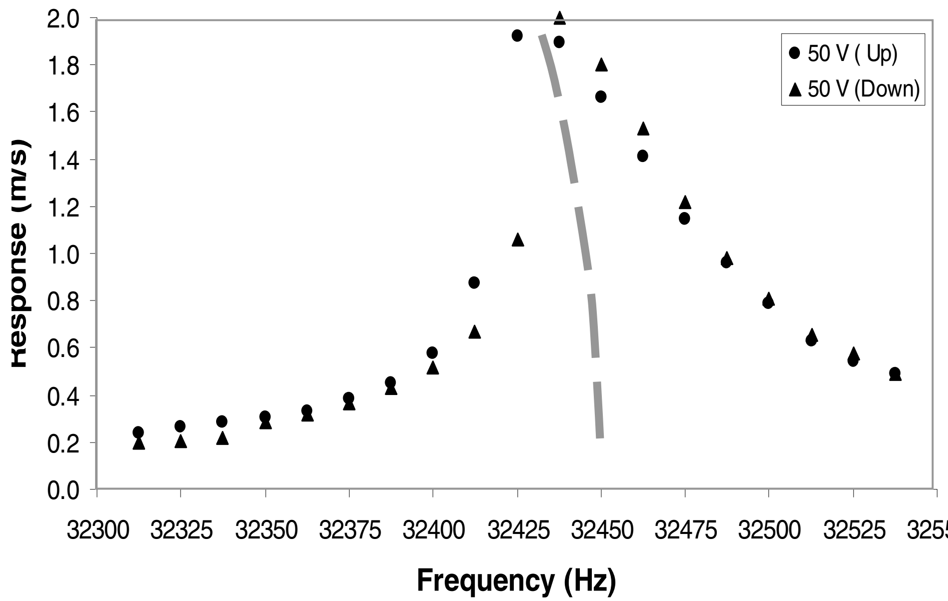
Effect of Tuned Bar on Response Characteristic (Case II: Excitation 50 V)

Transducer



Transducer -1.5 wavelength bar horn system





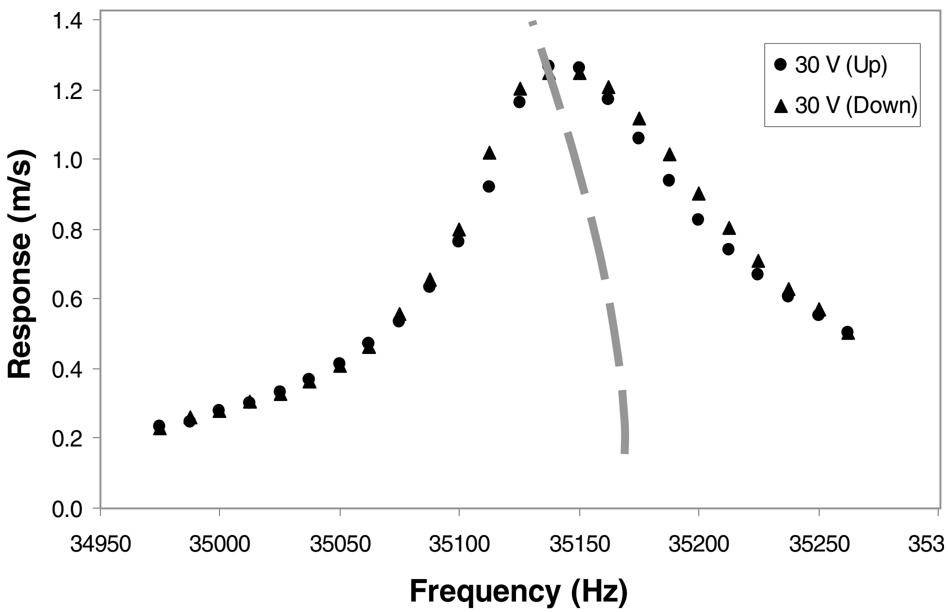
The transducer exhibits a clear softening response characterised by the jump phenomenon and an unstable region.

The transducer-bar horn system still shows a softening characteristic, however no unstable region is detected.

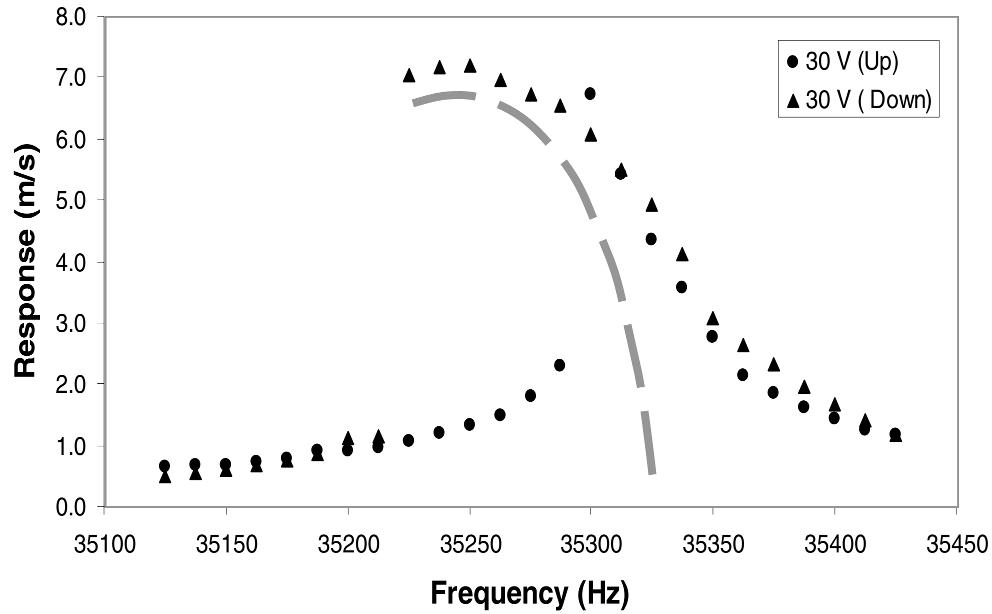
Effect of Blade on System Response Characteristic (Case I: Half-wavelength Blade; Excitation 30 V)

Transducer

Transducer -half wavelength blade system



The transducer exhibits a softening characteristic



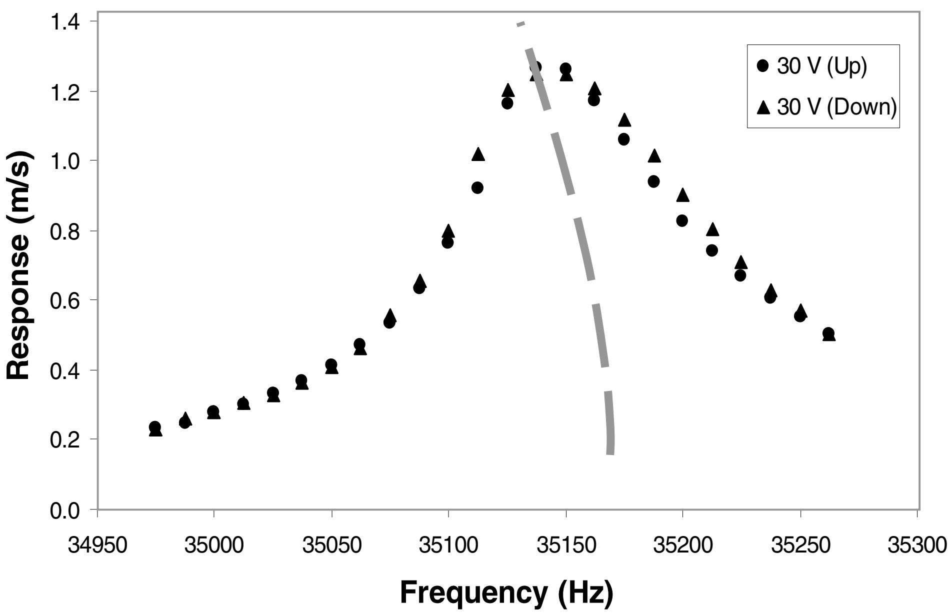
The transducer-blade system exhibits a clear softening response characterised by the jump phenomenon and a wide unstable region.

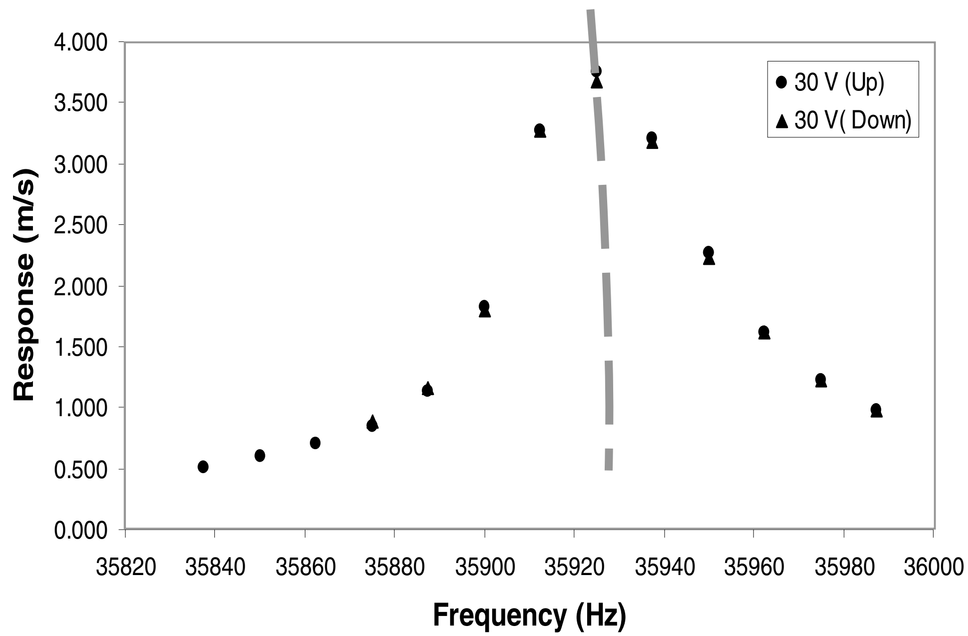
UNIVERSITY of GLASGOW

Effect of Blade on System Response Characteristic (Case II: One wavelength Blade; Excitation 30 V)

Transducer

Transducer-one wavelength blade system

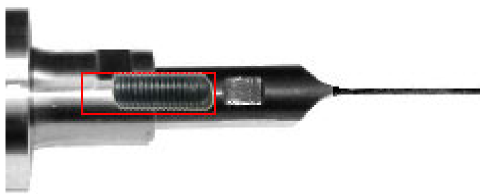


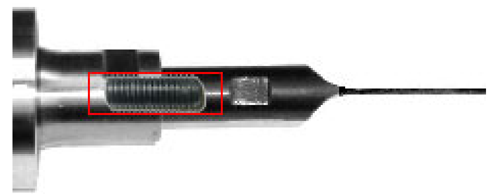


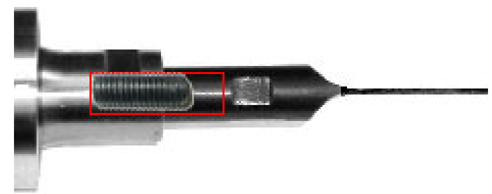
The transducer-blade system shows a near linear response characteristic

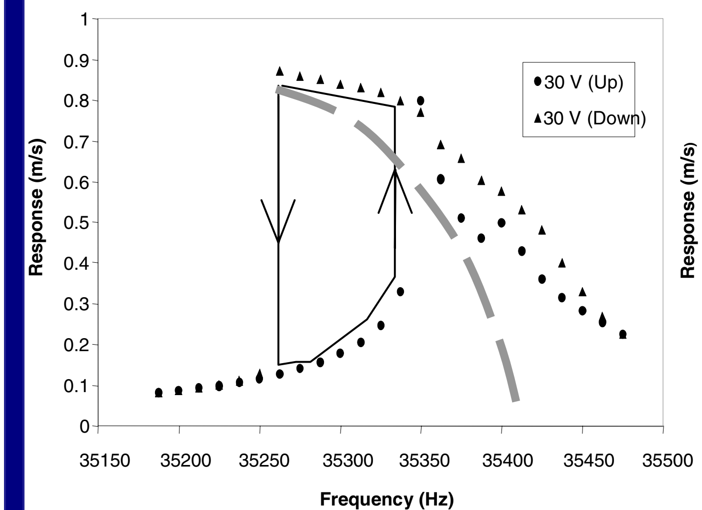
Investigation of Stud Configuration for Nonlinear Cancellation Coupling

UNIVERSITY *of* GLASGOW

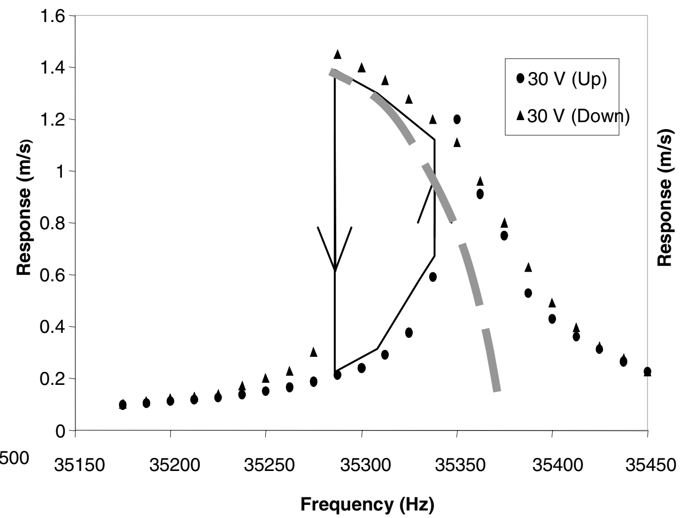




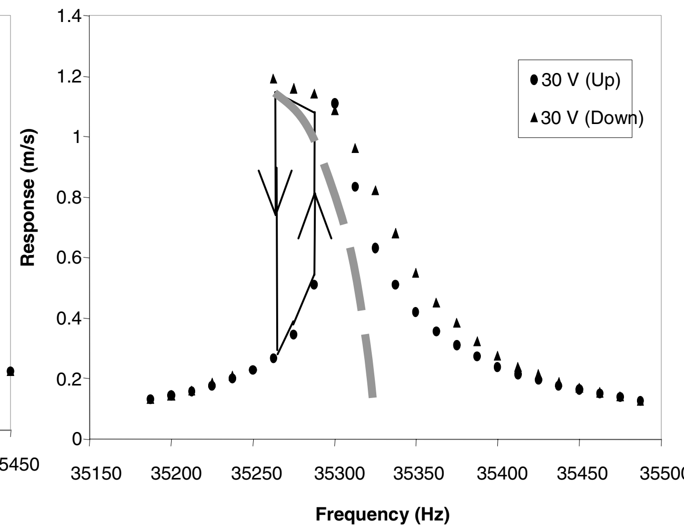




Threaded stud fully-screwed into the blade-base



Threaded stud half-screwed into the blade-base



Threaded stud fully-screwed into the transducer-base

UNIVERSITY of GLASGOW

Conclusions

- FE analysis is an effective numerical method for design and analysis of ultrasonic tools.
- Strategies have been proposed to reduce stress at blade failure locations by geometric modifications (by blade profile and block geometries).
- The nonlinear behaviour of ultrasonic cutting systems has been characterised experimentally.
- Strategies to reduce the effects of nonlinear reponses by cleaning the response spectrum have been proposed.
- Strategies to reduce nonlinearity by Nonlinear Cancellation Coupling have been proposed.