I. ABSTRACT
This paper presents an investigation of predictive modeling of space structures for structural health monitoring (SHM) with piezoelectric wafer active sensors (PWAS) transducers. The development of a suitable SHM system for complex space structure is not trivial; creating a robust SHM capability requires at least: (a) flexible accommodation of numerous configurations; (b) detection of damage in complex multifunctional structures; (c) identification if mechanical interfaces are properly connected. To realize this, we propose a predictive modeling approach using both analytical tools and finite element method (FEM) to study the health status of the structure, the power and energy transduction between the structure and the PWAS. After a review of PWAS principles, the paper discusses the modeling and the power and energy transduction between structurally guided waves and PWAS. The use of guided wave (GW) and the capability of embedded PWAS to perform in situ nondestructive evaluation (NDE) are explored. FEM codes are used to simulate GW of 2D and 3D space structure using the commercials software ABAQUS. PWAS transducers placement at different location on a flat plate and on an isogrid panel was simulated. The signal scattered by a crack emerging from the hole is simulated. Predictive modeling of power and energy transduction is discussed using an analytical approach. This model of 2-D power and energy transduction of PWAS attached to structure allows examination of power and energy flow for a circular crested wave pattern. Wave propagation method for an infinite boundary plate, electromechanical energy transformation of PWAS and structure, and wave propagation energy spread out in 2-D plate are considered. The parametric study of PWAS size, impedance match gives the PWAS design guideline for PWAS sensing and power harvesting applications.

II. INTRODUCTION
Structural health monitoring is an emerging technology with multiple applications in the evaluation of critical structures. The goal of SHM research is to develop a monitoring methodology that is capable of detecting and identifying, with minimal human intervention, various damage types during the service life of the structure. A typical monitoring system would be one which enables non-invasive, continuous monitoring of the structure. Numerous approaches have been utilized in recent years to perform structural health monitoring; they can be broadly classified into two categories: passive and active methods.

Active SHM systems using interrogative Lamb waves are able to cover large areas from a single location making such systems cost effective and efficient. Another advantage is that Lamb waves provide through-the-thickness interrogation which allows detection of internal defects in materials. Piezoelectric wafer active sensors (PWAS) are used for active SHM technique. However, Lamb waves present some difficulties: they are dispersed, at a given frequency, and thus several modes can propagate at different speeds. Work has been done to establish analytically the dispersion curves [1-6], to validate experimentally [7] and to study the effect of dispersion over long distances [8]. The phenomena of interaction between the ultrasonic wave and the defect and/or the structure, leading to a complex signature (reflection, diffraction, mode conversion, etc.) must be simulated to achieve a specific response signal actually received by sensor. Many authors have already investigated the interaction of Lamb modes with a single defect like crack, notch or circular cavity. Some of them used analytical [9] or semi-analytical [10] resolutions. Whereas many authors [11-17] chose the most popular computational tool used in engineering research and industrial design, the finite element method (FEM). Finite element method (FEM) modeling has a role to play in simulating elastic wave propagation associated with acoustic phenomena and ultrasounds problems.

This paper presents the use of guided wave (GW) and the capabilities of embedded PWAS to perform in situ nondestructive evaluation (NDE) are explored. FEM codes are used to simulate GW of 2D and 3D space structure. PWAS
transducers placement at different location on a flat plate and on an isogrid panel was simulated. The signal scattered by a crack emerging or not from the hole is simulated. Predictive modeling of power and energy transduction is discussed using an analytical approach. This model of 2-D power and energy transduction of PWAS attached to structure allows examination of power and energy flow for a circular crested wave pattern.

III. ANALYTICAL MODEL

Piezoelectric wafer active sensors (PWAS) are the enabling technology for active and passive SHM systems. PWAS couples the electrical and mechanical effects through the tensorial piezoelectric constitutive equations

\[ S_y = s_{ykl}T_{kl} + d_{kl}E_k \]
\[ D_j = d_{jkl}T_{kl} + \varepsilon_{k}^T E_k \]

where, \( S_y \) is the mechanical strain; \( T_{kl} \) is the mechanical stress; \( E_k \) is the electrical field; \( D_j \) is the electrical displacement; \( s_{ykl} \) is the mechanical compliance of the material measured at zero electric field (\( E = 0 \)), \( \varepsilon_{k}^T \) is the dielectric permittivity measures at zero mechanical stress (\( T = 0 \)), and \( d_{kl} \) represents the piezoelectric coupling effect. PWAS utilize the \( d_{31} \) coupling between in-plane strain and transverse electric field. A 7-mm diameter PWAS, 0.2mm thin, weights around 78 mg and costs around $1 each. PWAS are lightweight and inexpensive and hence can be deployed in large numbers on the monitored structure.

PWAS transducers can be serve several purposes [18]: (a) high-bandwidth strain sensors; (b) high-bandwidth wave exciters and receivers; (c) resonators; (d) embedded modal sensors with the electromechanical impedance spectroscopy method. By applications types, PWAS transducers can be used for (i) active sensing of far field damage using pulse-echo, pitch-catch, and phased-array methods, (ii) active sensing of near field damage using high frequency EMIS and thickness gage mode, and (iii) passive sensing of damage-generating events through detection of low-velocity impacts and acoustic emission at the tip of advancing cracks.

The analytical modeling of the pitch-catch process between two PWAS transducers separated by a distance \( x \) was carried out in frequency domain in four steps: (i) Fourier transform the time-domain excitation signal \( V_r(t) \) taken into the frequency domain spectrum, \( \tilde{V}_r(\omega) \); (ii) calculate the frequency-domain structural transfer function at the receiver location, \( G(x,\omega) \); (iii) multiply the structural transfer function by frequency-domain excitation signal to obtain the frequency domain signal at the receiver, i.e., \( \tilde{V}_r(x,\omega) = G(x,\omega)\cdot\tilde{V}_r(\omega) \); (iv) perform inverse Fourier transform to obtain the time-domain receiver signal, \( V_r(x,t) = \text{IFFT}(\tilde{V}_r(x,\omega)) = \text{IFFT}(G(x,\omega)\cdot\tilde{V}_r(\omega)) \).

In this paper, the main interest is in symmetric fundamental mode (\( S_0 \)) and anti-symmetric fundamental mode (\( A_0 \)). For Lamb waves with only two modes (\( A_0 \) and \( S_0 \)) excited, the structure transfer function \( G(\omega) \) is given by Eq. (99) of ref. [18], page 327, which gives the in-plane strain at the plate surface as

\[ \varepsilon_i(x,t) = -i\frac{\alpha_T}{\mu} (\sin k^r a) \frac{N_S(k^r)}{D_S(k^r)} e^{-(k^r x - \omega t)} \]
\[ -i\frac{\alpha_T}{\mu} (\sin k^a a) \frac{N_A(k^a)}{D_A(k^a)} e^{-(k^a x - \omega t)} \]

So, can be written as

\[ G(\omega) = S(\omega)e^{-a^2x} + A(\omega)e^{-a^2x} \]
\[ S(\omega) = -i\frac{\alpha_T}{\mu} (\sin k^r a) \frac{N_S(k^r)}{D_S(k^r)} \]
\[ A(\omega) = -i\frac{\alpha_T}{\mu} (\sin k^a a) \frac{N_A(k^a)}{D_A(k^a)} \]
\[ D_S(\omega,d) = (k^2 - \beta^2)^2 \sin\beta d + 4k^2\alpha^2 \cos\alpha d \sin\beta d \]
\[ D_A(\omega,d) = (k^2 - \beta^2)^2 \sin\alpha d \cos\beta d \]
\[ N_S = k\beta(k^2 - \beta^2) \cos(\alpha d) \sin(\beta d) \]
\[ N_A = k\beta(k^2 - \beta^2) \sin(\alpha d) \cos(\beta d) \]
\[ \alpha^2 = \frac{\omega^2}{c_p^2} - k^2 \]
\[ \beta^2 = \frac{\omega^2}{c_s^2} - k^2 \]

where \( a \) is the half length of the PWAS, \( 2d \) is the half thickness of the plate, \( \tau_0 \) is the shear stress between PWAS and the plate, \( \mu \) is Lamé’s constant, \( k^r \) and \( k^a \) are the wavenumbers for \( S_0 \) and \( A_0 \) respectively, \( x \) denotes the distance between the two PWAS transducers, \( k \) represents the wavenumber for \( S_0 \) or \( A_0 \) accordingly, \( c_p \) and \( c_s \) are the wave speed for pressure wave and shear wave respectively. In the transfer function, it could be observed that \( S(\omega) \) and \( A(\omega) \) will determine the amplitude of \( S_0 \) and \( A_0 \) mode. In both \( S(\omega) \) and \( A(\omega) \) terms, there is \( \sin(k^r a) \) and \( \sin(k^a a) \), which represent the tuning effect.

The wave speed dispersion curve is obtained by solving Rayleigh-Lamb equations, which are transcendental equations that require numerical solution. The usual form of Rayleigh Lamb equations is as

\[ D_S(\omega,d) = 0 \quad \text{and} \quad D_A(\omega,d) = 0 \]
After getting the wave speed dispersion curve, the wavenumber for each frequency component i.e. \( \xi = \omega/c \) is known. Thus, all the terms involved in the plate transfer function could be solved, and the plate transfer function \( G(\omega) \) is obtained. After the plate transfer function \( G(\omega) \) is obtained, the excitation signal is Fourier transformed.

IV. FEM MODELING

In non-destructive evaluation (NDE), a common understanding is that the ultrasonic scanning technique can usually detect damage. Furthermore, the fundamental anti-symmetrical mode \( (A_0) \) is preferable and more sensitive to damage because its wavelength is shorter than that of the \( S_0 \) mode at the same frequency. However, the \( A_0 \) mode exhibits more dispersion at low frequencies. The FEM simulation of the \( A_0 \) mode requires fine spatial discretization with substantial computational cost for the sake of the short wavelength. In contrast, the mode shapes of the \( S_0 \) mode are simpler and the stresses are almost uniform throughout the thickness of the plate at low values to the frequency and plate thickness product. For these reasons, the two modes \( S_0 \) and \( A_0 \) were selected in this study to evaluate the interaction of Lamb waves with different defects.

The analytical modeling, the finite element modeling and the experimental results for a 1-mm thick aluminum plate with a dimension of 44 x 12 mm² are shown in Figure 1. \( S_0 \) and \( A_0 \) mode wave packages could be observed. The wave speed of \( S_0 \) mode is higher than the \( A_0 \) mode, so the \( S_0 \) wave packet is picked up earlier than the \( A_0 \) wave packet. Furthermore, the different results show a near-perfect match.

A. 2D modeling of realistic rib-stiffened structure

The geometry of the model was chosen based on the approximate rib spacing, skin thickness, and rib dimensions found in the isogrid structures described in various publications [19, 20]. Application of the SHM method on a complex structure was investigated utilizing a simulated satellite panel from two aluminum (6061-T6) plates with a dimension of 44 x 12 mm². In order to realistically represent a complex satellite structure, an isogrid frame composed of sixty-four 50 x 9 mm² cutouts with a 5 mm wall thickness was modeled.

For the purpose of this study, Lamb wave are considered, which travel in wave guides and activate the entire thickness of the structure. In plates, symmetric and anti-symmetric wave modes are possible and travel at velocities dependent on frequency, and the thickness of the plate. The dispersion characteristics of a 3-mm thick plate are shown in Figure 2. As shown in this figure, for a frequency below 550 kHz, only two modes are present: the fundamental symmetric mode \( S_0 \) and the anti-symmetric mode \( A_0 \). Moreover, for a frequency below 650 kHz, the \( S_0 \) mode travels faster than the \( A_0 \) mode.

The commercial finite element analysis software ABAQUS was used to investigate the same geometry as described before for a 1D model (Figure 3). Because of the dynamic wave propagation events, ABAQUS explicit was used for its time calculation efficiency. For model simplification and because the piezoelectric elements are not available in ABAQUS/Explicit, the actuation was applied as a pair of self-equilibrating forces. The geometry was meshed with C3D4R (plane strain element, 4-node bilinear, reduced integration). Preliminary 1D and 2D work on a simple plate indicated that the best match between experiments and FEM was obtained using the default viscous damping parameters of the ABAQUS software.

The time modulation applied to the self-equilibrating excitation forces was a 3 count 320-kHz smoothed tone burst; preliminary tests indicated that this excitation frequency generates well separated \( S_0 \) and \( A_0 \) wave packets.

Figure 4a presents a comparison between the finite element analysis results for a plate (without rib) and with one rib. The receiver PWAS (R-PWAS) is at 55-mm of the transmitter PWAS (T-PWAS), and the rib (5 mm x 9 mm) is on the middle of the plate. On this figure, the \( S_0 \) mode does not change, whereas of the \( A_0 \) mode does change. Moreover, some mode conversion and some reflections can be observed when the rib is present. Figure 4b presents a comparison between the finite element analysis results for a plate (without rib) and with two ribs. The R-PWAS is at 110-mm of the T-PWAS, and the first rib is at 25 mm and the second rib is at 70 mm of the T-PWAS. On this figure, the \( S_0 \) mode does not change, whereas the \( A_0 \) mode does change. Moreover, some mode conversion and some reflections can be seen in the signal when two ribs are present in the path between the T-PWAS and the R-PWAS.

In order to detect damage in the structure, a crack was modeled at the corner on the rib and the plate (Figure 5). The size of the crack is 0.5-mm length and 0.001-mm thick. Small changes in the signal received at R1 and R2-PWAS are observed.

Figure 6a presents a comparison of R1-PWAS signal in the pristine plate and in the plate with corner crack at rib 5. The \( S_0 \) mode does not change. The \( A_0 \) mode does change slightly with its magnitude decreasing a little in the case of the crack. Figure 6b presents the results for R2-PWAS: again, the \( S_0 \) mode does not change; the \( A_0 \) mode changes slightly: its magnitude decreases, but less than for the R1-PWAS.

This predictive 2D FEM analysis shows the importance of sensors positioning to achieve good crack detection in a complex structure.

B. 3D modeling of realistic rib-stiffened structure for space application

To test the application of the SHM method on a realistic 3D complex structure we considered a simulated rapid satellite panel consisting of two isogrid structures. Each isogrid was obtained by making 64 cutouts (50 x 50 x 9 mm³ with 5 mm wall thickness) in a 445 x 445 x 12 mm³ aluminum 6061-T6 plate. A bolt hole was drilled in the center of each grid (Figure 7). PWAS transducers were applied to the isogrid (Figure 7b). The R1-PWAS is at 55-mm from the T-PWAS, whereas the R2-PWAS is at ~77-mm from the T-PWAS. A small crack was simulated in one of the bolt holes (Figure 7c).
The excitation signal was again a 3-count 320-kHz smoothed tone burst. Figure 8 presents a comparison of the signals predicted for the pristine structure and for the structure with a cracked hole. Figure 8a shows the signal captured by R1-PWAS very clear signal change is observed due to the crack in the hole (time shift and magnitude decrease). Moreover, many modes conversion and many reflections are present in the 3D model which greatly complicates the analysis of these data. Figure 8b presents the predicted signals captured by the R2-PWAS: the signal change due to the crack is much less than R1-PWAS.

This 3D predictive FEM analysis shows the critical importance of sensors positioning for the detection of crack in a complex structure. The predictive modeling results presented here should be compared with actual experimental data taken an actual isogrid panel.

V. PREDICTIVE MODELING OF POWER AND ENERGY TRANSDUCTION FOR SHM APPLICATIONS

A preliminary analysis of the 1-D and 2-D power and energy transduction process for SHM applications was performed [21, 22] by considering (a) PWAS transmitter; (b) PWAS receiver; and (c) PWAS transmitter-receiver pair. Both 1-D linear PWAS and 2-D circular PWAS analytical models of wave propagation and power and energy transduction were based on the following assumptions: (a) ideal bonding connection between PWAS and structure; (b) ideal excitation source at the transmitter PWAS and fully-resistive external load at the receiver PWAS; and (c) axial and flexural wave propagation. The electrical active power, reactive power, and power rating for harmonic voltage excitation were examined. The parametric study of transmitter size and impedance, receiver size and impedance, and external electrical load gives the PWAS design guideline for PWAS sensing and power harvesting applications. The analysis was performed in the simplifying case of axial and flexural waves, which are easier to handle than the full guided-wave model. However, the principles of this exploratory study can be extended without much difficulty to the full multi-mode guided-waves. A brief summary of 2-D model is given next.

A. Circular PWAS Transmitter Power and Energy

The electrical energy of the input voltage applied at the PWAS terminals is converted through piezoelectric transduction into mechanical energy that activates the expansion-contraction motion of the PWAS transducer. This motion is transmitted to the underlying structure through the shear stress in the adhesive layer at the PWAS-structure interface. As a result, ultrasonic guided waves are excited into the underlying structure. The mechanical power at the interface becomes the acoustic wave power and the generated axial and flexural waves propagate in the structure.

It was found that the reactive electrical power required for 7-mm diameter circular PWAS excitation is orders of magnitude larger than the active electrical power. Hence, the power rating of the PWAS transmitter is dominated by the reactive power, i.e., by the capacitive behavior of the PWAS. We note that the transmitter reactive power is directly proportional to the transmitter admittance \( Y = i\omega C \), whereas the transmitter active power is the power converted into the ultrasonic acoustic waves generated into the structure from the transmitter under perfect bonding assumption. The power analysis indicated that the active power applied by the transmitter PWAS converts to circular crested wave power. Perfect electrical source and loss-less adhesive layer was assumed in this model and there is no loss during the electrical-mechanical-wave power transduction.

The power analysis also indicated that optimal axial and flexural wave excitation by PWAS can be obtained when the PWAS radius is an odd multiple of the half wavelength of particle wave modes. The geometric tuning can be obtained through matching between their characteristic direction and the half wavelength of the excited axial or flexural wave mode. Due to the tuning effects, a remarkable variation of active power with frequency is shown in analysis. We notice that the active power (i.e., the power converted into the ultrasonic waves) is not monotonic with frequency, but manifests peaks and valleys. As a result, that ratio between the reactive and active powers is not constant, but presents the peaks and valleys pattern. The increase and decrease of active power with frequency corresponds to the PWAS tuning in and out of various ultrasonic waves traveling into the structure.

Figure 9 presents the results of a parameter study for various radius circular PWAS sizes and frequencies. The resulting parameter plots are presented as 3D mesh plots. Figure 9a presents a 3D mesh plot of the power rating vs. frequency and transmitter radius: for a certain transmitter radius, the power rating increases when the frequency increases. For a given frequency, the power rating increases when the transmitter radius increases. These results are clarifying: to drive a 15-mm length PWAS at 1000 kHz with a 10 V constant voltage input, one needs a power source providing 10 W of power. Figure 9b shows the wave power that PWAS generates into the structure; tuning effect of transmitter size and excitation frequency are apparent; a larger PWAS does not necessarily produce more wave power at a given frequency! The maximum wave power output in this simulation is \( \sim 20 \text{ mW} \). The powers contained in the axial waves and flexural waves are given separately in Figure 9c and Figure 9d. In some PWAS SHM applications, a single mode is often desired to reduce signal complexity and simplify signal interpretation and damage detection. Figure 9c shows the frequency-size combinations at which the axial waves are maximized, whereas Figure 9d indicates the combinations that would maximize the flexural waves. These figures give useful guidelines for the choosing PWAS size and frequency values that are optimum for selecting a certain excitation wave mode. This study gives guidelines for the design of transmitter size and excitation frequency in order to obtain maximum wave power into the SHM structure.
B. Wave power and energy transfer from transmitter in structure

The power and energy of forward and backward axial and flexural waves remain constant in 1-D situation. However, the axial and flexural wave excited by circular PWAS transmitter spreads out. Kinematic analysis gives the displacement generated by a circular PWAS in terms of the axial and flexural displacement as with Bessel function. Bessel function can be approximated using the fact that it exhibits an asymptotic behavior after four or five cycles of the wavelength of the mode considered. The total axial and flexural wave is independent with the wave propagation distance \( r \). The displacement amplitude exhibits an asymptotic behavior with \( \sqrt{1/r} \).

C. Circular PWAS receiver

Receiver PWAS has a similar size tuning effect as transmitter PWAS. When propagating waves reach the receiver PWAS, receiver PWAS converts the wave energy to electrical energy and outputs a voltage signal. For sensing application, a high value of the output voltage is desired. The external electrical load such as oscilloscope resistance is set to high impedance. In this case, only a small amount of power and energy is picked up by PWAS. In power harvesting application, receiver PWAS with a matching external electrical load impedance can output the maximum power.

D. Circular PWAS Pitch-catch Power Analysis

The power and energy transduction flow chart for a complete pitch-catch setup is shown in Figure 10. There are three parts in the power flow: transmitter PWAS power and energy, wave propagation power and energy in structure, and receiver PWAS power and energy. In pitch-catch mode, the power flow converts from electrical source into piezoelectric power at the transmitter, the piezoelectric transduction converts the electrical power into the mechanical interface power at the transmitter PWAS and then into acoustic wave power travelling in the structure. The wave power arrives at the receiver PWAS and is captured at the mechanical interface between the receiver PWAS at the structure. The mechanical power captured is converted back into electrical power in the receiver PWAS and captured at the receivers electric instrument. The time-averaged electrical power, mechanical power at the transmitter and wave power can be calculated from the frequency response function. In a 2-D pitch-catch sensing simulation, we used an Aluminum alloy 2024 infinite plate with 1 mm thickness. PWAS transmitter and receiver were 7-mm diameter and 0.2-mm thickness. A 20-Vpp 100-kHz central frequency 3-count Hanning window tone-burst signal was applied to the transmitter. The receiver instantaneous voltage response was shown in Figure 11a. The fast axial wave was separated from the low speed flexural wave. The axial wave was non-dispersive and kept the shape of excitation signal. The flexural wave spread out due to the dispersive nature. The receiver RMS power, defined as \( RMS = \sqrt{\frac{\int V^2 dt}{r}} \), was calculated (Figure 11b). It is clear that the receiver RMS power is proportional with \( 1/r \).

VI. CONCLUSIONS

This paper presented an investigation of predictive modeling of space structures for structural health monitoring (SHM) with piezoelectric wafer active sensors (PWAS). The development of a suitable SHM system for complex space structure is not trivial; creating a robust SHM capability requires at least: (a) flexible accommodation of numerous configurations; (b) detection of damage in complex multi-functional structures; (c) identification if mechanical interfaces are properly connected. To realize this, we propose a multi-physics predictive modeling approach using both analytical tools and finite element method (FEM) to study the health status of the structure and the power and energy transduction between the structure and the PWAS. After a review of PWAS principles, the paper was discussed the modeling and the power and energy transduction between structurally guided waves and PWAS. The use of guided wave and the capability of embedded PWAS to perform in situ nondestructive evaluation were explored. FEM codes were used to simulate GW of a 2D and a 3D space structure using the commercial software ABAQUS. PWAS transducers placement at different location on a flat plate and on an isogrid panel was simulated. The signal scattered by a crack emerging from the hole was simulated.

Predictive modeling of power and energy transduction is discussed using an analytical approach. This model of 2-D power and energy transduction of PWAS attached to structure allows examination of power and energy flow for a circular crested wave pattern. Wave propagation method for an infinite boundary plate, electromechanical energy transformation of PWAS and structure, and wave propagation energy spread out in 2-D plate are considered. The parametric study of PWAS size, impedance match gives the PWAS design guideline for PWAS sensing and power harvesting applications.

The analytical model is expected to be extended to 3D circular PWAS analysis, and Bessel function will studied and included in future work to realize guided wave propagation between two circular PWAS transducers. For further study, the analytical modeling is expected to include damage in the plate structure using a non-linearity aspect. Moreover the non-linear element will be included in a finite element method to simulate two plate bonded with bolts.

VII. ACKNOWLEDGMENTS

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Figure 1: Comparison between analytical, FEM, and experimental signal receive from a PWAS (-150 kHz frequency excitation).
Figure 2: Dispersion curve for 3-mm thick aluminum 6061-T6 plate.

Figure 3: 2D geometry used in finite element modeling with sensors.

Figure 4: Influence of ribs on sensor signals (a) R1-PWAS at 55 mm from T-PWAS; (b) R2-PWAS at 110 mm from T-PWAS.
Figure 5: Modeling of corner crack at rib 5: (a) FEM mesh geometry; (b) Zoom-in showing densified mesh around crack.

Figure 6: FEM prediction of the influence of corner crack on sensor signal; (a) R1-PWAS at 55 mm from T-PWAS; (b) R2-PWAS at 110 mm from T-PWAS.

Figure 7: 3D isogrid model (a) 3D view of the interior; (b) Zoom-in of the exterior view showing the position of the PWAS transmitter (T) and receiver (R) transducers; (c) Detail of cracked hole.
Figure 8: 3D FEN predictions of the influence of hole crack on sensor signal: (a) R1-PWAS at 55 mm from T-PWAS; (b) R2-PWAS at ~77 mm from T-PWAS.

Figure 9: PWAS transmitter under constant voltage excitation (a) power rating; (b) wave power; (c) axial wave power; (d) flexural power.
Figure 10: Power and energy flow in a PWAS pitch-catch configuration.

Figure 11: Pitch-catch signal with a receiver PWAS (a) at different distance from a transmitter PWAS, (b) RMS power of a receiver at different distance.