COMPUTATIONS OF ELECTRO-ACOUSTIC EFFICIENCY OF UNDERWATER TONPILZ TRANSDUCER

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1. INTRODUCTION

SONAR use acoustics for detection, tracking, and classification of underwater targets. The sound generation, reception, and its propagation are the most fundamental principles of sonar. Active sonars purposely generate sound in the desired direction and detect targets by echo-location and passive sonar intercepts the sound radiated by the targets. ASW is the most challenging operational environment for a military sonar, with an objective to detect and track the submarine with minimum error, so that the target is precisely hunted when the weapon is launched. ASW active sonars evolved tremendously from few kilo-meter range direct path detection to over the horizon detection using bottom bounce propagation paths. Modern ship sonars use large bow mounted transducer arrays for bottom bounce detection. The system requirements and the platform constraints dictate the type of array and the transducer. Cylindrical array of Tonpilz transducers is widely used in bow mounted ship sonars.

Tonpilz is one of the most popular type of underwater transducer used in weapon sonars. Tonpilz is a well-established design and its mathematical, equivalent circuit, and Finite Element (FE) models are available for customizing the design. The high-power handling, inherent directionality, ease of design and manufacturing, and compactness make Tonpilz an ideal choice for ship-borne active sonars. Source Level (SL) is an equipment parameter in active sonar[1], which is critical in deciding the figure-of-merit of sonar. Source level of array depends on array size, frequency of operation, power handling, and electro-acoustic efficiency of the transducer. The requirement of long detection ranges forces the transducer to operate at higher power for longer pulse durations. Heat generation due to inherent losses in the transduction material (PZT) is the limiting factor that restricts electro-acoustic transducer from handling high power[2]. This requirement of high-power handling can be sufficiently compensated by enhancing the efficiency of the transducer.

The paper describes the numerical model of a Tonpilz to compute its electro-acoustic efficiency. The engineering design of a typical Tonpilz is presented first. The components used in the construction of Tonpilz is introduced in this section. Next, the numerical model of engineered Tonpilz is discussed. The model is analyzed for efficiency and the critical components that affect the efficiency of Tonpilz is presented here. Then, efficiency of Tonpilz is computed using an alternate method and the results are compared with the numerical model.

2. TONPILZ DESIGN

Tonpilz is a piston type transducer evolved from the Langevin design. Simplest mathematical model of Tonpilz is a ‘mass-spring-mass’ system operates in the vicinity of resonance. The resonance and the vibration amplitude of the system are governed by the end masses and the stiffness of the spring. The end masses in Tonpilz are often called as head (m_1) and tail (m_2); head is the radiating mass and tail provide necessary inertial backing to the head. The PZT stack replaces spring in Tonpilz, and it drives the end masses, and the head radiate acoustic energy into the medium. Axially polarized PZT rings of same cross-section are coaxially stacked using glue joints to drive the end masses. The rings in the stack are connected mechanically in series to reduce its stiffness and electrically connected in parallel. Electrodes are glued in between the rings to electrically excite the stack. The stack is insulated from the metal end masses using FRP washers.

PZT is the most critical component in the design of electro-acoustic transducer. The stresses in the PZT's becomes the first constraint even though the stresses in the other components are sometimes higher. Allowable tensile and compressive stresses in PZT4 during dynamic operations are 10 MPa and 100 MPa, respectively[3]. Piezoceramics are generally weak in tensile load and recommended to operate under pre-compressive stress to prevent any tensile load during the dynamic operations. The different transducers use different mechanism to apply the pre-stress. Tonpilz use a stress rod which pass through the axis of PZT stack and bolted at the end masses to pre-compress the stack. The end masses and stack assembly are inserted into an encapsulated metal housing case. The encapsulation over the casing ensures the water-worthiness of the transducer. The cut view of an engineered Tonpilz (model) is shown in Fig. 1. The components used for the construction of Tonpilz are listed in Table 1.

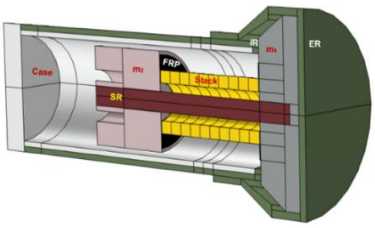

Figure 1. Cut view of Tonpilz

Table 1. Components used in the construction of Tonpilz

Tonpilz component	Symbol	Material
Head Mass	m_1	metal
Tail Mass	m_2	metal
Piezoelectric Stack	Stack	hard PZT
Stack Washer	FRP	FRP
Stress Rod	SR	metal-alloy
Stress Rod Nut	Nut	metal
Metal Casing	Case	metal-alloy
Encapsulation	ER	rubber
Interface Rubber	IR	rubber

The PZT stack is excited in the same frequency band at which the sonar is designed for. The magnitude of driving voltage is limited by the allowable voltage to the transducer. Transducers in active sonars are characterized by its resonance frequency (f_r), Transmitting Voltage Response (TVR), Source Level, directivity, power handling capacity, bandwidth, and electro-acoustic efficiency (η). Source Level is a measure of maximum pressure at one-meter distance along Maximum Response Axis (MRA) and measured in dB reference one micro-Pascal. Directivity Index (DI) is the dB measure of directionality of the transducer and it is zero for non-directional transducer. The maximum allowed electrical power (W_e) is limited by the volume of PZT used, also it should not exceed the product of allowed voltage and current to the transducer. The allowed voltage is limited by allowable electric field, cavitation, allowable stress, fatigue, and thermal limitation of the transducer. Electro-acoustic efficiency is the measure of the ratio of output acoustic power (W_a) to the input electrical power. In dB scale, the efficiency, η, is expressed as

$$\eta = 10 \log\left(\frac{W_a}{W_e}\right). \qquad [1]$$

The efficiency and SL are related by[4]

$$SL = 170.8 + DI + 10\,log(W_e) + \eta. \qquad [2]$$

DI is the dB measure of the ratio of acoustic intensity along the MRA, $I_0(r)$, at far-field distance r to the average acoustic intensity, $I_{avg}(r)$, integrated over surface area of sphere of radius r. DI depends on the array size and frequency and in symbols,

$$DI = 10 \log\left(\frac{I_0(r)}{I_{avg}(r)}\right). \qquad [3]$$

The allowable electrical power, DI, and efficiency of the transducer altogether determines the source level. SL is a system parameter and it is essential to maximize in noise limited active sonars for longer detection ranges. For a fixed frequency and array size, SL can be increased by increasing the input power (within the limit of allowable level) or by increasing the efficiency of transducer. The higher power significantly affects the endurance as well as the life of the transducer.

3. FINITE ELEMENT MODELLING

A fluid loaded Tonpilz is modelled numerically to compute its electro-acoustic efficiency. The model is developed in COMSOL-Multiphysics[5]. All the features in the real hardware are exactly captured in the model except for the glue joints, electrodes, pre-compression in the PZT stack, and the hydrostatic load. The transducer is modelled in 3D and structural-acoustics physics is solved to compute the dependent variable. Helmholtz wave equation is solved in the pressure acoustics physics to compute the acoustic pressure. The transducer is analyzed as a boundary value problem and solved in the frequency domain.

All design components are constructed in the COMSOL using built-in geometries. The fluid loading is simulated by modelling a water sphere all around the transducer. The domains are discretized using tetrahedral mesh elements and cubic order interpolation function is used to capture the variation of dependent variable in each mesh element. The mesh element size and order or interpolation function are chosen based on the convergence analysis. The mesh size is defined as parameter and its size is normalized with reference to the analysis frequency. A Perfectly Matched Layer (PML) is modeled at the outer surface of spherical water domain. PML absorbs the incoming wave from the computational domain and simulates free-field computation domain. The PML thickness is mathematically scaled to the incoming wavelength. An exterior field is defined at the boundary layer inside the PML to compute the dependent variable outside the physical domain. The cut view of fluid loaded Tonpilz used for the analysis is shown in Fig. 2. The meshed model is shown in Fig. 3.

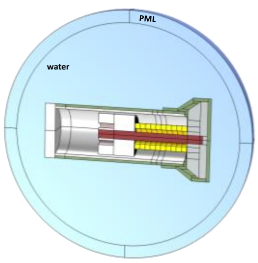

Figure 2. Model of fluid loaded Tonpilz

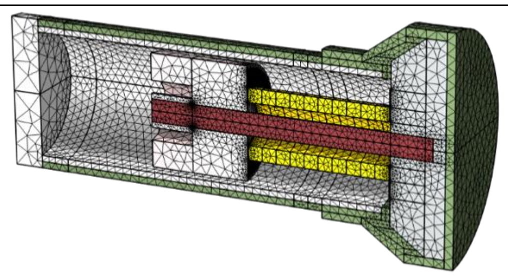

Figure 3. Meshed model

The numerical tool for computing electro-acoustic efficiency is verified in two stages. First, Tonpilz used for the efficiency computation is analyzed for its voltage response and beam width and compared with the experiments. This confirms the accuracy of model for geometry, boundary and excitation conditions, and materials used. Next, a pulsating sphere of arbitrary dimension is modelled. Both analytical and numerical models are developed. The model is analyzed for radiated acoustic power and the results are compared with the theory. This verifies the tool for the computation of radiated acoustic power, W_a, from the vibrating structures.

3.1. Model Validation

The model shown in Fig. 2 is analyzed for TVR and beam width. Standard material losses are assigned to the PZT stack. Encapsulant is modelled as hyper-elastic material with isotropic losses. The TVR is computed by measuring the acoustic pressure at far-field and then reduced to one-meter distance. The hardware is characterized in an open tank using comparison calibration method. The TVR and beam width (-3 dB) are measured and compared with the model. The normalized TVR and beam width are shown in Fig. 3 and Fig. 4, respectively. The frequency axis of TVR is normalized with reference to the resonance frequency of the model. The TVR value is scaled with respect to the model peak TVR. The frequency axis in Fig. 4 is normalized to the frequency at which the radiating head size equals to the λ/2. Good agreement is observed between the model and experiment. The resonance predicted by the model is observed slightly greater than the hardware and this shift is due to the presence of glue joints, electrodes, and stack pre-compression in the hardware.

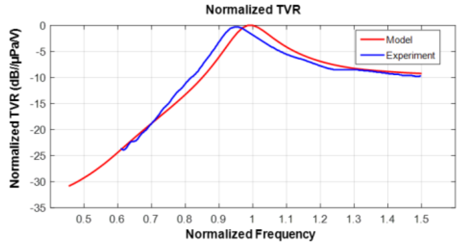

Fig. 3. Normalized TVR

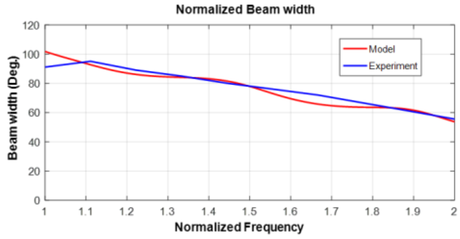

Fig. 4. -3 dB beam width

3.2. Model Verification

A monopolar radiating source is modelled to compute the acoustic intensity and power. The sphere of radius b is excited with a radial velocity $u_0 e^{-j\omega t}$ (u_0 is the velocity amplitude of sphere oscillating with an angular frequency ω). The governing equation for a monopole source is expressed as

$$\nabla^2(rp) = \frac{1}{c^2}\frac{\partial^2(rp)}{\partial t^2} \quad [4]$$

where c is the sound speed in water and p is the pressure at the field-point r.

The wave equation is solved to derive the expression for the pressure. The pressure and particle velocity, u, are derived by solving Eq. 4 with appropriate boundary conditions,

$$p(r,t) = \frac{u_0 \rho_0 b^2 j\omega}{(1-jkb)r} e^{-j(\omega t - k(r-b))} \quad [5]$$

$$u(r,t) = \frac{-u_0 b^2}{(1-jkb)r}\left(\frac{1-jkr}{r}\right) e^{-j(\omega t - k(r-b))}. \quad [6]$$

The acoustic impedance, $Z(r)$, is the ratio of pressure to the particle velocity, which is a complex quantity with real value measures the acoustic resistance and the imaginary represents the acoustic reactance. The acoustic impedance at r is expressed as[6]

$$Z(r) = \rho_0 c\left[\frac{jkr}{(1+(kr)^2)} + \frac{(kr)^2}{(1+(kr)^2)}\right]. \quad [7]$$

The driving point impedance is the acoustic impedance at $r = b$, and $Z(b)$ in symbols,

$$Z(b) = \rho_0 c\left[\frac{jkb}{(1+(kb)^2)} + \frac{(kb)^2}{(1+(kb)^2)}\right]. \quad [8]$$

The time-average active intensity is

$$I = \frac{u_0^2 b^4 \rho_0^2 \omega^2}{2\rho_0 c r^2 (1+(kb)^2)}. \quad [9]$$

The total radiated acoustic power, c, is obtained by integrating the acoustic intensity all over the surface of sphere in the field and expressed as

$$\Pi = \frac{u_0^2 b^4 \rho_0^2 \omega^2}{2\rho_0 c(1+(kb)^2)} 4\pi. \quad [10]$$

The same elastic sphere is modelled in COMSOL. The sphere is radially excited with unit velocity amplitude in the frequency band 100 Hz to 50 kHz. A spherical water domain is modelled all around the elastic sphere. PML is modelled to simulate unbounded fluid domain. The meshed model of a fluid loaded pulsating sphere is shown in Fig. 5. The pressure and particle velocity are computed at some far-field distance to measure the impedance. The intensity components are integrated all over the surface of fluid sphere at far-field to measure the acoustic power. The model results are compared with the theory and shown in Fig. 6. The model result shows excellent agreement with theory and the numerical tool is verified for computing radiated power from the vibrating structures.

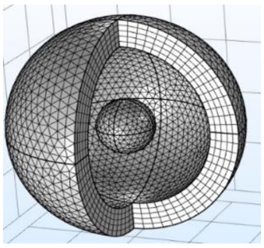

Figure 5. Meshed model of fluid loaded pulsating sphere

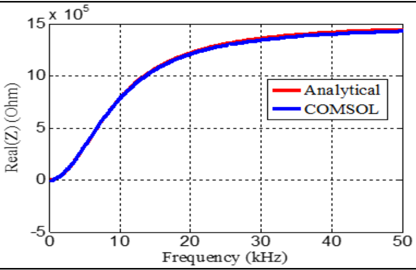

Figure 6. a. Radiation resistance of a pulsating sphere at $r = b$

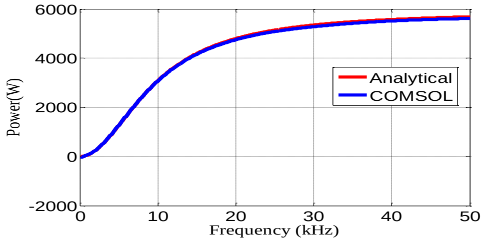

Figure 6. b. Acoustic power radiated from a fluid loaded pulsating sphere

3.3. Efficiency Computation of Tonpilz

Next, Tonpilz is analyzed in COMSOL for electro-acoustic efficiency. The stack is excited with one-volt rms (V_{rms}) and electrical parameters like conductance (G), impedance (Z), and phase (ϕ) are measured. The input electrical power is calculated using

$$W_e = V_{rms} G. \quad [11]$$

Acoustic power, W_a, is computed by integrating the components of acoustic intensity all over the surface of water sphere at far-field. Water is modelled as homogenous non-absorbing fluid. The radiated power from a piston vibrator is proportional to its radiation resistance (R_r) and square of vibration velocity[6]. The normalized radiation impedance (Z_r) for a piston source is shown in Fig. 7. The impedance is plotted against normalized diameter of piston, $2ka$. As the normalized diameter increases, the radiation resistance approaches to the characteristic's impedance of the medium and the reactance reduces to zero. The normalized radiation resistance becomes the characteristic impedance when $2ka$ equals to 4. The electric and acoustic power radiated by the Tonpilz are computed and plotted against normalized diameter and shown in Fig. 8. Both electric and acoustic power peaks at resonance, therefore the efficiency of the transducer is not expected to have a peak at the resonance.

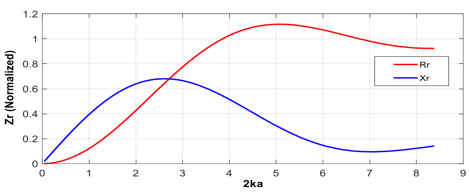

Figure 7. Radiation impedance of a piston vibrator

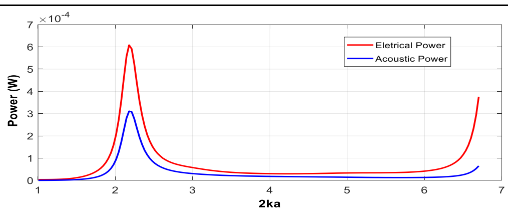

Figure 8. Electric and acoustic power of Tonpilz

The computed efficiency of the Tonpilz is shown in Fig. 9. The efficiency spectrum has two distinct peaks in the operating band. The first peak coincides with the antiresonance frequency of the Tonpilz and the second peak corresponds to the lowest frequency at which the radiation resistance becomes the characteristic impedance of the medium. The efficiency of the transducer can be increased by optimally choosing these two frequencies. The experiment on piezoelectric materials confirms that the operation near antiresonance need less power than at resonance for generating the same vibration velocity[2]. The Tonpilz used for the analysis is designed for broad-band applications and the efficiency varies from 50 to 60 percentage in its operating band.

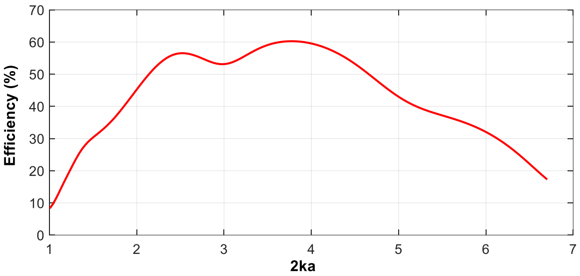

Fig. 9. The computed efficiency of a broad-band Tonpilz transducer

Next, parametric analysis is carried out to find the effect of different design components on efficiency. The material losses in the PZT are not considered as design parameter, whereas the dimensions of PZT ring and stack used are chosen as design parameter. The ring and stack dimensions are designed to have maximum coupling coefficient in the longitudinal mode of vibration.

The effect of head mass material on transduction efficiency is studied. The head mass in Tonpilz provides necessary impedance matching between the stack and medium. The characteristics impedance of the stack is higher compared to the impedance of water. The head mass in the Tonpilz reduces the impedance contrast between stack and the medium. Therefore, the material selection of head mass is identified as critical in deciding the efficiency of Tonpilz. The ratio of characteristic impedance of stack to that of water is approximately 14[4]. The average (geometric mean) characteristic impedance of between stack and the medium is approximately 6 Mrayls. The efficiency is computed for few different head mass materials and the results are shown in Fig. 10. It is observed that the efficiency attains maximum when the characteristic impedance of the head is close to the average impedance between the stack and water.

The effect of encapsulant thickness, t_r, and interface rubber on efficiency are studied. The rubber encapsulant prevents the water ingression and make the transducer water-worthy. The dimensions and the type of encapsulant are design parameters and are decided by the hydrostatic and the environment conditions where the transducer is designed for. The efficiency is studied for different encapsulation thickness and shown in Fig. 11. The analysis recommended to use minimum rubber thickness based on the required depth of operation for maximizing the efficiency. The interface rubber prevents the hard contact between the head and metal casing under hydrostatic load. This portion compresses under hydrostatic pressure and operates in a pre-compressed mode during the dynamic operation of the transducer. In the model, pre-compression is not simulated. The efficiency of Tonpilz is analyzed with and without interface rubber and no significant change in efficiency is observed.

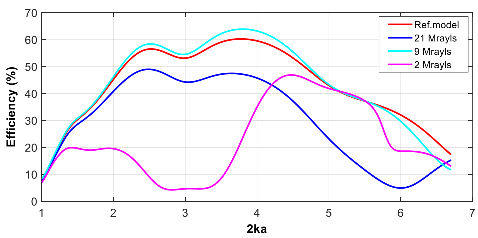

Figure 10. Efficiency by varying head mass material

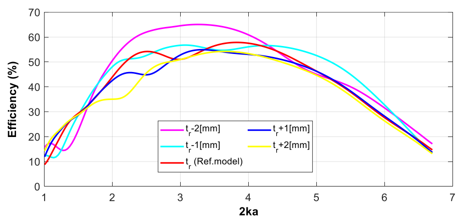

Figure 11. Efficiency by varying encapsulation thickness

FRP washers are used at the end of the stack to electrically insulate the PZT form the end masses. The same washers are also used to fine tune the resonance of the device to the desired frequency. The model is analyzed to find the effect of FRP thickness and its losses on efficiency. The effect of FRP thickness on efficiency is shown in Fig. 12. The thickness is varied relative to the reference model, t_f. FRP thickness is identified as critical parameter on efficiency. It is recommended to use very thin FRP to maximize the efficiency. Also, recommended to use minimum loss FRP or equivalent material to maximize the efficiency.

Based on the analysis, the Tonpilz used for the study is optimized for the maximizing the efficiency. The following design modifications are made in the optimum model: anti-resonance of the transducer is shifted towards the radiation resistance peak, head mass material and encapsulant thickness are optimally selected, and thin FRP washers are used. The efficiency computed for the optimum model is compared with the reference model and shown in Fig. 13. The efficiency of optimum model increased by more than 15% in the operating band. This increase in efficiency enhances the SL approximately by 1 dB or reduces the power handling by 20% for a fixed SL. The power reduction reduces the input drive level and stresses and enhance the life and endurance of the transducer.

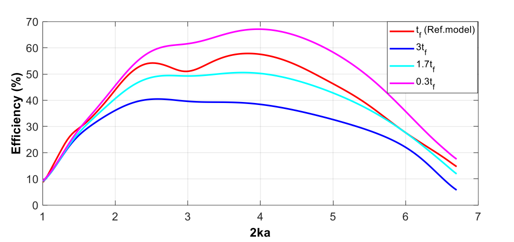

Figure 12. Effect of FRP thickness on efficiency

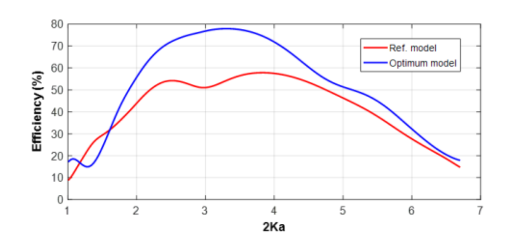

Figure 13. Efficiency of optimum model

4. EQUIVALENT CIRCUIT MODEL

This section describes the method of determining the electroacoustic efficiency of a Tonpilz transducer using lumped-parameter electrical equivalent circuit model. The transducer operating in the vicinity of fundamental mode resonance is represented by the Butterworth-VanDyke (BVD) electrical equivalent circuit[7] and shown in Fig.14. C_0 is the clamped capacitance, and R_1, L_1 and C_1 are the electrical equivalents of mechanical loss, mass and compliance, respectively. The parameters R_1 and L_1 include radiation impedance (Z_r) also. The mechanical impedance Z_m^E, with its electrical port short-circuited, is transformed to its electrical equivalent impedance Z_1 through the electromechanical transformation ratio N^7.

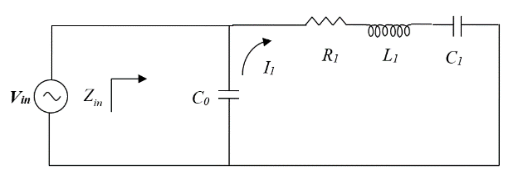

Figure 14. BVD equivalent electrical circuit model

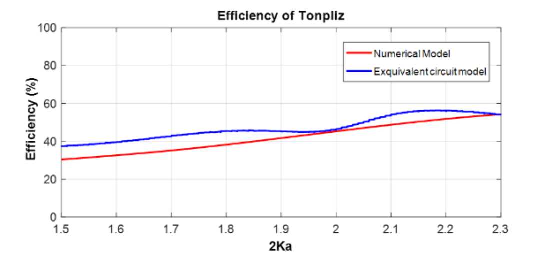

Figure 15. Efficiency of Tonpilz: COMSOL vs Equivalent circuit

$$\frac{Z_m^E}{N^2} = Z_1 = \left[R_1 + \frac{1-\omega^2 L_1 C_1}{j\omega C_1}\right]. \qquad [12]$$

The impedance of the electrical branch is $Z_0 = 1/j\omega C_0$ and the net input electrical impedance of the circuit is,

$$Z_{in} = \frac{Z_0 Z_1}{Z_0 + Z_1}. \qquad [13]$$

The current (I_1) passing through the radiation impedance in the mechanical branch is transformed into surface velocity of the radiating face, which in turn produces acoustic pressure in water. It is assumed that the radiating face of the transducer exhibits piston mode vibrations with uniform velocity. The surface velocity (U_0) of an electric field transducer depends on the voltage (V=V_{in}) across the mechanical branch and is given by,

$$u_0 = \frac{F}{Z_m^E} = \frac{NV}{Z_m^E} \qquad [14]$$

where, F is the force at the radiating surface on the piston, written as $F = NV$ according to equivalent circuit analogy.

The amplitude of on-axis acoustic pressure generated by a piston radiator with surface area A^h, at distance r in the far field is written as[6],

$$P(r) = \frac{j\omega\rho u_0 A^h}{2\pi r}. \qquad [15]$$

Rearranging above equation yields

$$P(r) = \frac{j\omega\rho A^h V}{2\pi r\, NZ_1}. \qquad [16]$$

From the axial pressure, on-axis acoustic intensity, I_a is computed and it is equated to the isotropic equivalent intensity I_o over a sphere of radius r, through the Directivity Factor (*DF*) as given by,

$$I_o = \frac{I_a}{DF}. \qquad [17]$$

The acoustic power, W_a, is computed from the average acoustic intensity and input electric power using Eq. 11. The efficiency is linear scale is expressed as

$$\eta = \frac{W_a}{W_e}. \qquad [18]$$

The efficiency computed using equivalent circuit model is compared with COMSOL and shown in Fig. 15.

5. CONCLUSIONS

Engineered Tonpilz transducer is analyzed in COMSOL for electro-acoustic efficiency. The intensity components are integrated in the numerical model to compute the total radiated acoustic power. The input electric power is computed from the electrical conductance and the drive voltage. The efficiency is computed from the power and plotted as function of normalized wave number. The efficiency of Tonpilz has two distinct peaks: first peak corresponds to its anti-resonance frequency and the second peak is at the frequency at which the radiation resistance of piston vibrator approaches to the characteristic impedance of the medium. The significance of different design parameters of Tonpilz on acoustic efficiency is also studied. The critical design components have identified and recommendations have made for maximizing the efficiency. The numerical model results are compared with the equivalent circuit model.

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