Design and Development of Power Generation System for Thermo-Acoustically Driven Devices

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Abstract. This paper explores the emerging field of thermo-acoustic devices, specifically focusing on developing robust bidirectional turbines. Amidst growing concerns about climate change, rising energy demands, and the urgent need for alternative solutions, the study highlights the underexplored domain of bidirectional turbines within thermo-acoustic systems, offering a crucial pathway toward cleaner and more sustainable technologies, thereby providing commercialization potential. It identifies a significant gap in dedicated investigations regarding the interaction, efficiency, and challenges associated with bidirectional turbines and adopts a comprehensive methodology integrating analytical modelling, computational fluid dynamics simulations, and practical experimentation. An axial bidirectional turbine is carefully selected, designed, and optimized using advanced tools such as MATLAB R2016a and CAD software, including PTC Creo 5.0 and Solidworks 2023. The validity of the CAD model is verified through ANSYS 16.2 CFX simulations, followed by experimental validation to corroborate and enhance theoretical insights. The conclusions drawn from this study offer valuable recommendations for further research and practical implementations.

1 Introduction

In today's world, where environmental issues and energy shortages are pressing concerns, the search for green and cost-effective energy solutions is more critical than ever. Thermoacoustic power generation is a promising answer to this challenge, offering benefits like using sustainable working mediums and effectively tapping into low-grade heat. Over the past thirty years, extensive research has highlighted the significant potential of thermoacoustic heat engines (TAHEs) in various applications, from refrigeration to electricity generation [1, 2, 3].

At the heart of thermoacoustic power generation lies the thermoacoustic electrical generator (TAEG), which combines a TAHE with an acoustic-to-electric converter. These...
components work together through acoustic coupling, where heat energy is converted into acoustic power within the TAHE and then transformed into electricity through the acoustic-to-electric conversion mechanism. This approach has gained attention as researchers strive to improve the efficiency of converting thermal energy into electricity [4].

Thermoacoustic systems are attractive because they adapt to different heat sources, including industrial waste heat, solar energy, and excess heat from electronic systems [5, 6]. They have few moving parts and are environmentally friendly, making them advantageous. Thermoacoustic power generators primarily consist of two components: the thermoacoustic heat engine, which converts heat into acoustic power, and an acoustic-to-mechanical or acoustic-to-electric power converter, which transforms acoustic power into usable energy [7]. While traditional electromagnetic devices [8, 9, 10], like loudspeakers and linear alternators, have been used for acoustic-to-mechanical conversion, their effectiveness decreases at larger scales. Therefore, researchers are exploring alternative methods such as piezoelectric materials [5, 11], magneto-hydro-dynamic devices [9, 12], and bi-directional turbines [13, 14, 15] as potential solutions for this crucial conversion process.

Piezoelectric materials are primarily used for small-scale applications, typically in the milliwatt (mW) range, with an acoustic-to-electric efficiency of 20% to 30% [6]. Magneto-hydrodynamic devices utilize electrically conductive or inductive fluids. While they can achieve maximum acoustic-to-electric efficiency of 40% [1], they face limited adoption due to challenges related to the gas-liquid interface, such as the impedance mismatch between the thermoacoustic engine's working gas and the liquid used in the interface.

Among electromagnetic devices, loudspeakers and linear alternators are the most common. Although more cost-effective, loudspeakers are restricted to low-power production with an acoustic-to-mechanical efficiency of around 60% [9]. On the other hand, linear alternators operate at higher mean gas pressures and dynamic pressure ratios, resulting in more considerable acoustic-to-electric efficiencies and higher output powers, such as 68% at 4.69 kW [9]. However, they have limitations, including the reciprocating motion's zero velocity point, which leads to intermittent electricity generation. Additionally, they have large acoustic impedance, requiring complex matching between the thermoacoustic engine, the linear alternator, and the electric load [16]. Moreover, maintaining significant electric output at low frequencies necessitates large strokes or strong magnetic fields, both presenting challenges. Large strokes are constrained by the need to maintain seal gaps, limited spring tolerances, and the counteracting forces they produce. Strong magnets, the alternative, are heavy and costly. Mechanical issues associated with the reciprocating motion of large moving masses also limit linear alternators. Higher power units require increased cooling rates, imposing a cap on the maximum power rating that can be adequately cooled.

Bi-directional turbines (BDTs) have been introduced to thermoacoustic applications to address the limitations of existing techniques. BDTs are turbines that convert the linear oscillating motion of the flow into a unidirectional rotational motion, eliminating the zero velocity point. Integrating this technology into thermoacoustic power generation offers several advantages. BDTs have low acoustic impedances and don't need their mechanical resonance frequency to match the engine’s operating frequency. Furthermore, their 3D printing capability reduces manufacturing costs, with reported power generation in Oscillating Water Column (OWC) applications reaching up to 500 kW [8]. BDTs operate without significant cooling requirements and don't rely on expensive magnets for operation. Additionally, these turbines do not need extensive cooling systems and do not rely on costly magnets. They have shown effectiveness in converting wave energy in OWC applications, where the movement of water in seas and oceans [17] creates an oscillating air column. This air column's energy is then transformed into mechanical power within the turbine. Various types of bi-directional turbines, including Wells turbines [13, 18], axial impulse turbines [19, 20, 21], and radial impulse turbines [18, 22], have been utilized in OWC power plants.
In comparing different types of bi-directional turbines for thermo-acoustic systems, the axial impulse turbine stands out as the most promising option, unlike the Wells turbine, which has a simple design but relatively low efficiency, especially in scenarios where the input velocity is insufficient to generate the required tangential force, the axial impulse turbine offers higher efficiency ratings of up to 50% [21]. Despite its more complex geometry compared to the Wells turbine, the axial impulse turbine's efficiency potential justifies the intricacies involved in its design. Additionally, the axial impulse turbine boasts better-starting characteristics [13], addressing concerns about weak starts encountered with the Wells turbine. While its blade design may depend on varying angles for optimal efficiency, the overall benefits of higher efficiency and improved starting characteristics make the axial impulse turbine a preferred choice for integration into thermo-acoustic systems.

Conclusively, the paper explores the feasibility of generating electricity using bidirectional turbines within thermoacoustic systems, both theoretically and in practical applications. It aims to determine the necessary input values for the turbine to convert acoustic power into electricity in thermoacoustic power generation efficiently. To address these inquiries, a numerical model is developed and optimized for a CAD design of a bi-directional turbine. This optimized numerical model is then analyzed using a Computational Fluid Dynamics (CFD) simulation tool to validate its accuracy. Subsequently, experiments are conducted to assess the viability of the proposed study, with the findings and conclusions presented after the paper.

2 Numerical modeling

The foundational framework for the preliminary design of the proposed axial impulse bidirectional turbine in this research draws inspiration from the work conducted by Tim Kloprogge [7] in 2012. In preparation for numerical modelling, key input parameters were determined. These parameters include the tube diameter (Dtube) set at 0.15 m, the turbine diameter (Dturbine) established at 0.1 m, and the hub diameter (Dhub) fixed at 0.07 m. The blade friction (kb) was also defined as 0.97, and Euler's number (e) was calculated to be 2.41828. Blade inlet angle (α) was specified within the range of 10º to 30º, while the sound pressure level (SPL) spanned from 85 dB to 95 dB, encompassing the acoustic conditions for analysis.

Fig. 1. Velocity triangle profile.

Fig. 1. shows the velocity triangle to be used in the numerical modelling. In the analysis, 'v1' represents the absolute velocity at the inlet, indicating where the fluid exits the guide vane. At the same time, 'v2' signifies the absolute velocity at the outlet where the fluid exits the blades. Additionally, 'vr1' and 'vr2' denote the relative velocities at the inlet and outlet, respectively, perpendicular to 'β1' (blade inlet angle) and 'β2' (blade outlet angle). The guide
vane's inlet angle is denoted by 'α'. Since 'α' is smaller than the blade angle 'β', an additional velocity vector is introduced to accommodate this disparity. This additional blade velocity is termed 'vb', and 'Δvω' represents the tangential velocities at the inlet and outlet. Firstly, the cross-sectional areas of the tube and turbine are calculated, ensuring that the turbine's cross-sectional area remains smaller than the tube to enhance the input velocity. The cross-sectional areas are determined using the formulae:

\[
A_{\text{tube}} = \frac{\pi}{4} * D_{\text{tube}}^2
\]

\[
A_{\text{turbine}} = \left(\frac{\pi}{4} * D_{\text{turbine}}^2\right) - \left(\frac{\pi}{4} * D_{hu}^2\right)
\]

Next, the input velocity, denoted as 'v1', is computed as shown in Eq. 3:

\[
v1 = \frac{A_{\text{tube}}}{A_{\text{turbine}}} \times vo
\]

where 'vo' represents the average air velocity passing through the turbine, calculated as \(v_{ac} \times 0.707\). The acoustic velocity 'v_{ac}' is determined by the formula given below:

\[
v_{ac} = \frac{SPL}{20 \times log_{10}(e)}
\]

where 'SPL' denotes the sound pressure level in dB and 'e' is a constant approximately equal to 2.71828. For turbine efficiency (η), an inlet angle 'α' of 25º is utilized, computed as:

\[
\eta = 0.5 \times \left[\frac{\cos^2 \alpha}{2} \times (1 + kb)\right]
\]

Here, 'kb' represents the blade friction factor, indicating the energy lost due to air friction along the turbine blades. Subsequently, the blade velocity 'vb' and the blade inlet angle 'β' are calculated as

\[
v_b = v_1 \times \frac{\cos \alpha}{2}
\]

\[
\beta = \tan^{-1}\left(\frac{v_1 + \sin \alpha}{v_1 + (\cos \alpha - v_b)}\right)
\]

The tangential velocity (Δvω), volume in the blade section (V), mass of the air in the blade section (m), and time for the air to pass through the blade section (t) are then determined using appropriate formulae followed by the computation of the tangential thrust (Pt) using the value of the mass flow rate. Subsequently, the blading work (W_b) is determined, representing the work done by the turbine. Energy going through the blades (Eb) and turbine efficiency (η) are computed using relevant formulas, and the circumference (φ) and rotational speed (rpm) of the turbine are then calculated. Finally, considering the typical efficiency of a generator averages around 80%, the output work of the generator (W_G) is determined as

\[
W_G = 0.8 \times W_B,
\]

where 'W_B' represents the blading work obtained earlier.

### 2.1 Parametric Study

The methodology described in previous section was implemented using MATLAB R2016a. The calculations were translated into MATLAB code for analysis, including turbine efficiency, blading work, blade velocity, guide vane angle, tangential velocity, energy through blades, rotational speed, and generator work. The parametric evaluation considered rotor blade angles ranging from 10 to 30 degrees and sound pressure levels from 85 to 95 dB.
The results of the parametric evaluation of various parameters previously mentioned are presented through graphs for clarity and interpretation as shown in Fig. 2.

**Fig. 2.** From left to right, top to bottom: (a) Turbine efficiency vs. Rotor blade angle, (b) Blade work vs. Rotor blade angle, (c) Blade Velocity vs. Rotor blade angle, (d) Guide vane blade angle vs. Rotor blade angle, (e) Tangential velocity vs. Rotor blade angle, (f) Energy vs. Rotor blade angle, (g) RPM vs. Rotor blade angle, (h) Generator work vs. Rotor blade angle
Figure 2(a) illustrates the relationship between turbine efficiency and rotor blade angles, indicating a trend of decreasing efficiency with increasing angles. Figure 2(b) shows the impact of rotor blade angles on blading work, with distinct patterns suggesting optimal angles for efficient work output. Similarly, Figures 2(c-h) depict relationships between blade velocity, guide vane angles, tangential velocity, energy throughput, RPM, and generator work with rotor blade angles. These visual representations offer valuable insights into the performance characteristics of the axial impulse turbine.

3 Design and Manufacture of Bi-directional turbine

The turbine model includes three main parts: an upstream stator, a rotor, and a downstream stator. The rotor's tip diameter is 100 mm with a hub-to-tip ratio of 0.7 and 20 blades. Both stators feature 17 guide vanes arranged in a mono-vane configuration. Each guide vane has a camber line composed of a straight segment and a circular arc. Additionally, an elliptic cone is attached at the entrance of both stators to direct the flow toward the stator blades. Detailed dimensions for the turbine components are provided in Tables 1, 2, and 3.

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<th>Ser</th>
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<td>2</td>
<td>Rotor blade circle arc radius (mm)</td>
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<td>3</td>
<td>Rotor blade inlet/exit angle (mm)</td>
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<td>Leading/trailing edge circle arc radius (mm)</td>
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Table 1. Rotor parameters

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Table 2: Inlet Guide Vanes Parameters

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Table 3: Outlet Guide Vane Parameters
The assembly comprises meticulously engineered components: a rotor, inner and outer guide vanes, a calibrated shaft, a sturdy hub, and carefully designed outer cones. It epitomizes the project's design goals, blending precision engineering with optimal functionality. The sectional view offers a detailed understanding of how these elements intricately interact within the assembly.

Fig. 3. Complete assembly description (left to right): Outer cone, hub cone, Inlet guide vane, Rotor, shaft, and Outlet guide vane

3.1 CAD Design and CFD Simulations

CAD tools like PTC Creo 5.0 and Solidworks 2023 were used to create detailed CAD models of the rotor, inlet guide vanes, outlet guide vanes, hub, and inner/outer cones. These CAD models provided a comprehensive prototype, aiding in understanding how theoretical calculations were practically implemented.

3.1.1 Mesh details

To initiate the detailed design process, Turbogrid tailored sophisticated hexahedral meshes were chosen specifically for the intricate blade passages commonly found in rotating machinery. Leveraging ANSYS 16.2 software, the automation of mesh generation significantly enhanced efficiency and precision. The Inlet Guide Vane mesh provided a detailed depiction of the vane's shape and effectively captured surrounding flow dynamics. Similarly, the Rotor mesh facilitated thorough flow pattern analysis due to its pivotal role in fluid dynamics. The Outlet Guide Vane mesh effectively captured fluid dynamics as it exited the component. Maintaining a controlled expansion rate of 1.3 through edge-regulated mesh, element growth ensured computational efficiency and appropriate resolution in critical areas. This systematic approach underscored a commitment to accurately represent and integrate complex geometries, demonstrating a dedication to detailed design and precise engineering in advanced computational design.
<table>
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<th>Software</th>
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<th>Number of Elements</th>
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### 3.1.2 Boundary conditions

After the meshing process was completed, the Turbogrid files were integrated into the ANSYS CFX platform to establish a comprehensive simulation environment. This was crucial for capturing the continuous rotational motion of all the components.

The boundary conditions for the inlet guide vane were configured to represent a stationary domain. The inflow boundary, facing the rotor, simulated the incoming airflow using an expression generated in CFX-Pre, defined as given in Eq. 8.

\[
U_0 + A \times \sin(2\pi ft)
\]  

(8)

where \(U_0 = 7 \text{ m/s} \) (mean velocity), \(A = 10 \text{ m/s} \) (velocity amplitude), and \(f = 50 \text{ Hz} \) (frequency). These settings ensured conservative heat transfer, mass, and momentum flux, facilitating the understanding of the interaction between the stationary guide vane and the rotating rotor. Similarly, the boundary conditions for the outlet guide vane mirrored those of the inlet guide vane, also configured to represent a stationary domain. The outflow boundary simulated the outgoing airflow of the guide vane at a pressure of 1 atm. These settings accurately represented the interactions between the stationary outlet guide vane and the rotating rotor, providing insights into the fluid dynamics as the airflow exited the thermoacoustic system.

For the rotor, interface conditions between different domains, such as rotor to inlet guide vane and outlet guide vane to rotor, were used as incorporated settings for general connection and transient rotor-stator interactions. These conditions facilitated smooth interaction between the rotating and stationary components, capturing the intricate dynamics of the thermoacoustic system. The blade, hub, and shroud boundaries for both the rotor and guide vanes were defined with specific wall conditions, including adiabatic heat transfer, no-slip wall for mass and momentum, and smooth wall roughness.
3.1.3 CFD Results

The observed simulation results (see Fig. 4) in the fluid flow pertains to its behavior as it navigates through the components of the turbine, particularly the inlet guide vane, rotor blade, and outlet guide vane. The fluid flow follows a smooth trajectory as it passes along the inlet guide vane and beneath the rotor blade. This suggests that the initial stages of the flow process exhibit minimal disruption or turbulence, allowing for efficient energy transfer within the system. However, the presence of a minor loss, as noted along the outlet tip of the rotor blade and the outlet guide vane, indicates a deviation from the ideal flow behavior. This loss can be attributed to various factors, such as formation of vortices above the rotor blade. Since vortices are swirling patterns of fluid motion that can develop due to disturbances in the flow field, the potential formation of vortices above the rotor blade suggests a localized disruption in the flow pattern, which could hinder the efficient transfer of energy from the inlet guide vane to the rotor blade. The presence of these vortices highlights the intricate and complex nature of fluid dynamics within the turbine system. It emphasizes the need for a comprehensive evaluation of the flow patterns to identify and address potential areas of inefficiency or loss.

During the analysis of pressure contours, an intriguing phenomenon emerged, highlighting the dynamics within the system. Specifically, notable differences were revealed in the total pressure distribution surrounding the rotor in comparison to both the Inlet Guide Vane and the Outlet Guide Vane. This disparity in pressure values indicated a discernible energy dissipation attributed to the rotational motion of the rotor (see Fig. 5). Despite the maintenance of a relatively consistent pressure gradient throughout the process, the diminished total pressure surrounding the rotor significantly influenced the system's energy dynamics. This observation indicates the complex interplay between the rotating rotor and the encompassing fluid medium. The decreased total pressure signifies a conversion of kinetic energy into alternative forms, thereby hinting at the presence of inherent losses within the system. This phenomenon also highlights the intricate nature of fluid dynamics within the turbine setup. It thereby, creates the importance of considering not only the primary
components of the system but also the secondary effects arising from their interactions. By comprehensively understanding these dynamics, researchers and engineers can strive to optimize turbine performance and minimize energy losses, ultimately contributing to the advancement of turbine technology.

Fig. 5. Total pressure contours inside impulse blade turbine

4 Additive Manufacturing

The turbine components were fabricated through 3D printing, which included the outer hub, inner hub, rotor, and inner and outer guide vanes. Stereolithography (SLA) technology was employed, utilizing Acrylonitrile Butadiene Styrene (ABS) material with a 30% filling ratio to ensure structural integrity. An internal filling angle of 45ºC was set for optimal performance. Precision was paramount throughout the printing process, with a consistent printing speed of 3600 mm/min maintained. A low primary layer height of 0.5 mm was chosen to enhance the quality and resolution of the printed components.

5 Experimental Setup

The experimental setup involved 1/4 acoustic waves generated from an acoustic source, travelling through a resonator tube coupled with a generator and a voltmeter at one end and the acoustic source at the other. The acoustic source was connected to a computer receiving input from an acoustic tone generator. To generate the acoustic wave, a function generator was employed to produce controlled sine waves at frequencies of 40 Hz, 50 Hz, 60 Hz, and 70 Hz, amplified by a power amplifier (Model AK170) and directed to an electromagnetic speaker (Model TS6964-S). The acoustic wave was then transmitted to the Bi-directional Turbine through a resonator tube (1500mm long), aligned with one-quarter (1/4) and three-quarters (3/4) of the wavelength corresponding to each frequency. Calculations based on the wave equation, \( c = \frac{\omega}{k} \), where \( c \) represents the speed of sound (343 meters per second), \( \omega \) denotes the frequency, and \( k \) signifies the wavelength, ensured precise resonance with the resonator tube, optimizing energy transfer efficiency for enhanced mechanical power generation.
6 Results and Conclusion

During a series of extensive experimental trials spanning the frequency range of 40 to 80 Hz, the rotational behaviour of the bidirectional turbine displayed inconsistency, particularly within the frequency band of 59 to 63 Hz, corresponding to quarter wavelengths between 1429 and 1435 mm. Minor rotations observed during these trials suggested a potential proximity to the turbine's resonance frequency, requiring additional acoustic power to achieve resonance. The observed inconsistency within this frequency range indicated the turbine's sensitivity to specific acoustic frequencies, highlighting the need for careful tuning and optimization. Recommendations arising from these findings include adopting Polylactic Acid (PLA) material for 3D printing to enhance structural integrity, employing a more potent acoustic power source for improved efficiency, and exploring alterations in turbine geometry to improve performance. These adjustments aim to address observed inconsistencies and optimize the bidirectional turbine system.

The research delved into power generation, focusing on thermo-acoustic devices, amid concerns about climate change and energy needs. Spotlighting bidirectional turbines within thermo-acoustic systems, the project aimed to contribute to cleaner and sustainable technologies. It sought to unravel the complexities of converting thermoacoustic energy into electricity, mainly focusing on bidirectional turbines, addressing a noticeable gap in dedicated inquiries. Through a comprehensive approach integrating analytical modelling, computational fluid modelling, and practical experimentation, a selected axial bidirectional turbine underwent selection, design, and optimization using advanced tools like MATLAB R2016a and CAD software. The CAD model was validated through ANSYS 16.2 CFX simulations, followed by an experimental setup to corroborate theoretical insights. Recommendations provided serve as guides for further research and practical implementations, shedding light on bidirectional turbines in thermo-acoustic systems and paving the way for future advancements in sustainable power generation.

References


