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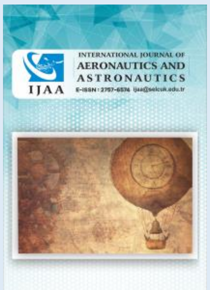

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Research Article / Araştırma Makalesi

Supersonic blowdown wind tunnel control using ABC optimized PID controller/ ABC ile optimize edilmiş PID kontrolcü kullanarak sesüstü üflemeli rüzgar tünelinin kontrolü

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ABSTRACT

Supersonic blowdown wind tunnels enable the testing of aircraft prototypes in the Mach 1.2 to 5 range, but these tunnels allow very limited test times due to their structure. In addition, once the wind tunnel system starts operating, the pressure in the tank where the air is stored changes constantly. This means that the parameters of the already nonlinear system dynamics are continually changing. To utilize this time effectively, fast-responding, stable and highly efficient controllers are needed. These controllers should be able to provide the required pressure in the settling chamber as fast as possible for the desired flow conditions in the test section. In these types of testbeds, Proportional-Integral-Derivative (PID) controllers are widely used because of their reliability, simplicity and ease of implementation. PID controllers can also provide fast and stable responses, as they can reduce the error, eliminate the steady-state error, and minimize the overshoot and oscillations. PID controllers only require the measurement of the error and the tuning of the coefficients, which can be performed manually or automatically. For a PID controller it is essential to optimize its coefficients to achieve the best performance and stability. There are different methods to tune a PID controller, such as trial and error, Ziegler-Nichols method, Cohen-Coon method, and optimization algorithms. This study proposes the use of an artificial bee colony in the optimization of PID coefficients used in the control of a supersonic blowdown wind tunnel. Because of complexity, an artificial bee colony is used to optimize PID coefficients with three different objective functions. The optimized coefficients are compared to gradient optimization results, and the best approach is determined.

ÖZET

Sesüstü üflemeli rüzgar tünelleri, Mach 1,2 ila 5 aralığında uçak prototiplerinin test edilmesini sağlar, ancak bu tüneller yapıları nedeniyle çok sınırlı test sürelerine izin verir. Ayrıca rüzgar tüneli sisteminin çalışmaya başlamasıyla birlikte havanın depolandığı tankın basıncı sürekli olarak değişmektedir. Bu da zaten doğrusal olmayan sistem dinamiğinin

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parametrelerinin sürekli olarak değişmesi anlamına gelmektedir. Bu problemlerle etkin bir şekilde başa çıkabilmek için hızlı tepki veren, kararlı ve yüksek verimli kontrolcülere ihtiyaç vardır. Bu kontrolcüler, test bölümünde istenen akış koşulları için dinlenme odasında gerekli basıncı mümkün olan en hızlı şekilde sağlayabilmelidir. Bu tür test yataklarında güvenilirlikleri, basitlikleri ve uygulama kolaylıkları nedeniyle Orantısal-İntegral-Türevsel (PID) kontrolcüler yaygın olarak kullanılmaktadır. PID kontrolcüler kararlı durum hatasını ortadan kaldırabilmeleri, aşım ve salınımları en aza indirebilmeleri gibi özellikleri ile hızlı ve kararlı yanıtlar sağlayabilirler. PID kontrolcüleri yalnızca hatanın ölçülmesini ve katsayıların ayarlanmasını gerektirir, bu da manuel veya otomatik olarak yapılabilir. Bir PID kontrolünde en iyi performansı ve kararlılığı elde etmek için katsayılarını optimize etmek çok önemlidir. Katsayıları belirlemek için Ziegler-Nichols yöntemi, Cohen-Coon yöntemi ve optimizasyon algoritmaları gibi farklı yöntemler kullanılmaktadır. Bu çalışma, bir sesüstü üflemeli rüzgar tünelinin kontrolünde kullanılan PID katsayılarının optimizasyonu için yapay arı kolonisi yönteminin kullanılmasını önermektedir. 3 farklı amaç fonksiyonu kullanılarak farklı PID katsayıları elde edilmiştir. Optimize edilen katsayılar gradyan optimizasyon sonuçlarıyla karşılaştırılmış ve en iyi yaklaşım belirlenmiştir.

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1. Introduction

The wind tunnel is the system that enables the tests of aircraft to be carried out on the ground with desired similarity parameters such as Mach number and Reynolds number. Supersonic Blowdown Wind Tunnels (SBWT) enable these tests to be performed at supersonic speeds in a laboratory environment for limited periods of time. It is necessary to obtain required pressure gradient between the inlet and outlet of the nozzle so that air flow at supersonic Mach numbers can be achieved. For this purpose, the air pumped into a storage tank is allowed to reach the settling chamber by leaving a regulation valve in a controlled manner. The air in the settling chamber passes through a nozzle and reaches the test section. By keeping the air pressure in the settling chamber constant, the wind tunnel can be operated at the desired Mach number. This critical operation can be performed properly by controlling the opening of the pressure regulation valve by means of a well-designed PID controller. High performance controller promises to provide maximum test duration by minimizing the rising and settling times without overshoot, to minimize the steady-state error, to compensate for the decreasing storage pressure and to prevent oscillations during the test. In literature, P, PI, PD, and PID controllers are tested, and it is seen that the PI and PID are superior to others [1]. It is seen that PI and PID controllers are effective but determining the coefficients is an important challenge [2]. To overcome this challenge, Linear Quadratic Gaussian (LQG) controller is tested. It is observed that the LQG control structure has a bigger overshoot and settling time than the PI controller in SBWTs. Therefore, it is proposed to use LQG with a correction method [3]. Fuzzy logic is proposed to improve the performance of the PI controller. Fuzzy logic takes the error and its derivative as input and affects the signal to the PI controller. It is declared that overshoot and setting time are reduced significantly [4]. Another Fuzzy-assisted PI structure is tested, where the fuzzy logic has two inputs as error and error derivative. The fuzzy logic output is summed with the simultaneously generated PI control signal to produce a new control signal. It is shown that the proposed method has less settling time but more overshoot [5]. When the Adaptive Neural-Network optimized Fuzzy-PI structure is tested, the optimization depends on the previously obtained database, it is issued that the overshoot, settling time, and steady-state error outcomes are better compared to conventional PI controller [6]. In the same way, Fuzzy-PD is used to control pressure and temperature for SBWT. It is declared that the proposed controller gives valuable performance [7]. The feed-forward controllers are tested for stagnation pressure control of SBWTs, and good accuracies are obtained [8]. In a different proposition, a Neural Network (NN)

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structure that represents an SBWT is created and this NN model is used to gain PID coefficients by using Genetic Algorithms (GA) for different conditions. The gain scheduled PID coefficients are tested, and the results are better compared to conventional PID controllers [9]. However, all these methods used to produce better results against PID are more complicated than PID, and methods such as fuzzy logic and genetic algorithms have limited operating ranges.

PID controllers are the most widely used control algorithm due to their simple implementation and usefulness [10]. Due to its high accuracy and stability, PID control systems have become an important component of engineering applications in various fields such as robotics, automotive, aerospace, industrial automation, and heating. In addition, there are many PID control applications for SBWTs in the literature. For this reason, the PID control approach is used in this study. However, while PID coefficients can be easily calculated for linear systems, it is difficult for highly nonlinear systems such as SBWTs. So, a meta-heuristic method is used to optimize PID coefficients.

Nowadays, meta-heuristic approaches are preferred as an alternative to classical methods to simplify optimization problems. Strategies derived from natural and biological phenomena, such as the foraging strategies of ants and other insects, are examples of strategies derived from nature. The strategy used was influenced by the clever behavior of insects, and swarms can be defined as any group of interacting agents or individuals [11, 12]. The group behaviors and cooperative actions displayed by insects when addressing complex challenges have inspired the concept of swarm intelligence, which has been instrumental in the development of contemporary metaheuristic methods. This concept relies on the understanding of how individuals can collaborate effectively by following simple rules. Particle Swarm Optimization [13], Ant Colony Algorithm [14], and Artificial Bee Colony (ABC) [15] are the most well-known algorithms in this field.

The Artificial Bee Colony (ABC) algorithm, a swarm intelligence-based algorithm, was proposed by Karaboğa in 2005 for multimodal and multidimensional numerical optimization problems [15]. It provides very remarkable results for continuous optimization problems [16, 17]. The Artificial Bee Colony (ABC) algorithm is used in this work to optimize the PID controller coefficients of a SBWT. During the optimization process, the controller's effectiveness is assessed using various performance criteria. In this context, regularly used objective functions such as Integral Absolute Error (IAE), Integral Squared Error (ISE) and Integral Time-weighted Absolute Error (ITAE) are examined. The impact of each objective function on controller performance is thoroughly investigated and compared to discovering the optimal PID coefficients that deliver the best system performance. As a result, this research not only focuses on the best PID controller design but also strives to give a comprehensive analysis of how different objective functions affect control system performance.

2. Supersonic Blowdown Wind Tunnel (SBWT)

The properties of supersonic vehicles can be mainly observed in two ways: Conducting a flight test using an actual vehicle prototype and conducting a wind tunnel test on a scaled vehicle model. There are different types of wind tunnels depending on their speed regime, geometry, working fluid, and the special purpose. In this study, blowdown type supersonic ($1.2 < \text{Mach} < 5.0$) wind tunnels are considered.

The SBWT system consists of the following main components: High pressure storage tank, control valve, settling chamber, nozzle, test section, and diffuser as shown in Figure 1.

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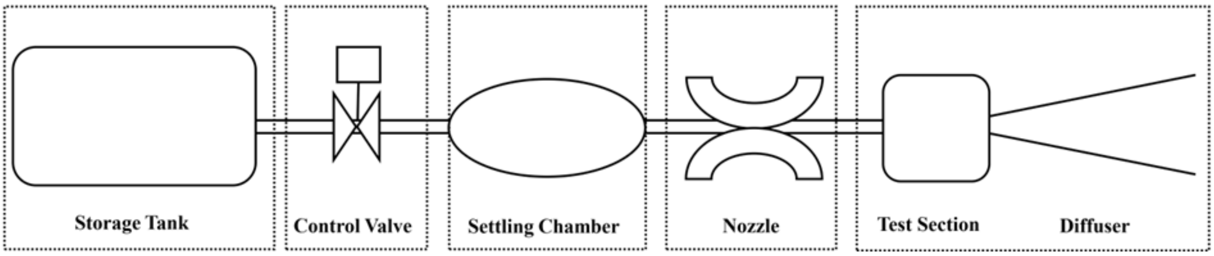

Figure 1. Diagram of supersonic blowdown wind tunnel

SBWTs operate intermittently using energy stored in high-pressure tanks. Firstly, at the beginning of the wind tunnel test, the control valve is opened and then the pressure difference creates a flow inside the wind tunnel, whereby air is drawn from the storage tank and exhausted into the atmosphere. The Convergent–Divergent (CD) nozzle plays a crucial role in accelerating the flow from near stagnation conditions to supersonic speeds. It is assumed that the stagnation flow parameters are obtained at the outlet of the settling chamber where the stagnation pressure and temperature are measured as the flow progresses through the nozzle, it is subjected to acceleration in order to ensure that the requisite flow parameters are attained for the desired conditions within the test section. [18]. In order to obtain different Mach numbers in the test section, the CD nozzle contour is changed and simultaneously the required stagnant flow parameters at the settling chamber are provided by the control valve. Therefore, the algorithm driving the control valve is extremely important for the efficient use of the limited experimental time of blowdown wind tunnels.

An SBWT is usually modelled using lumped parameters. In this method, the wind tunnel is divided into separate sections, each of which is then subjected to a separate analysis. This approach allows greater focus on specific accuracy criteria by treating each section in more detail [19]. Two control volumes are selected for its analysis: The storage tank and the settling chamber. The subsequent process involves utilising the fundamental principles of conservation - in particular those of mass, momentum and energy - and systematically applying them to the defined control volumes under consideration. Finally, the mathematical model of the SBWT is obtained by applying the conservation of mass and energy laws first to the reservoir and then to the settling chamber [20]. The equations used are listed below:

$$\frac{d\rho_{ST}}{dt} = -\frac{1}{V_{ST}}\dot{m}_{CV} \tag{1}$$

$$\frac{dP_{ST}}{dt} = -\frac{KR}{V_{ST}}T_{ST}\dot{m}_{CV} \tag{2}$$

$$\frac{d\rho_0}{dt} = \frac{1}{V_0}(\dot{m}_{CV} - \dot{m}_\star) \tag{3}$$

$$\frac{dP_0}{dt} = \frac{KR}{V_0}(T_{ST}\dot{m}_{CV} - T_0\dot{m}_\star) \tag{4}$$

$$\dot{m}_\star = \rho_\star A_\star V_\star = \sqrt{\frac{K}{R}\left(\frac{2}{\mathrm{K}+1}\right)^{\frac{K+1}{2(K-1)}}} A_\star \frac{P_0}{\sqrt{T_0}} \tag{5}$$

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In this context, the term "ρ" refers to air density, "V" refers to volume, "m" refers to mass, "$\dot{m}$"refers to mass flow,"P"refers to pressure, "T" " refers to temperature, "M"refers to Mach (speed of sound) number and "A"refers to cross-sectional area.

The indexes; "ST" denotes the storage tank, "CV" denotes the control valve, "0" denotes the settling chamber, "TS" denotes the test section and " $*$ " denotes the nozzle throat. "K" is the ratio of air specific heat to pressure and is taken as 1.4, "R"is the air gas constant and is taken as 287 [8].

T_{ST} (storage tank temperature) and T_0 (settling chamber temperature) are accepted as $288\ K$.The V_{ST} (storage tank volume) is taken as $2600\ m^3$and V_0 (settling chamber volume) is taken as $360\ m^3$ [8].

The "A_*"nozzle throat area is defined as follows:

$$A_\star = A_{TS} M_{TS} \left(\frac{5 + M_{TS}^2}{6} \right)^{-3} \tag{6}$$

where A_{TS} (test section area) is given as 2.25 m^2 [8]. M_{TS}refers to the air speed at test section.

The mass flow that pass through the control valve can be calculated by the equation given below [21]:

$$\dot{m}_{cv} = \rho_{CV} A_{CV} v_{CV} = \sqrt{\frac{2K}{R(K-1)}} \frac{P_{ST}}{\sqrt{T_{ST}}} A_{CV} \left(\frac{P_{CV}}{P_{ST}} \right)^{\frac{1}{K}} \sqrt{1 - \left(\frac{P_{CV}}{P_{ST}} \right)^{\frac{K-1}{K}}} \tag{7}$$

The maximum mass flow that pass through the control valve is achieved when the ratio of P_{CV} (pressure at control valve) to P_{ST} (pressure at storage tank) is equal to or greater than 0.5283.

In the event of a blockage in the flow, the mass flow is calculated using the equation provided in equation (7) for $P_{CV}/P_{ST} = 0.5283$ [8]. Temperature, pressure and density are assumed at ideal conditions.

Although the model of the SBWT is simplified through these approaches, it remains highly nonlinear. This nonlinear behavior adds complexity to the wind tunnel’s flow dynamics, requiring further investigation to accurately control and predict the flow.

3. PID Control

PID control system is an efficient and effective control system in literature [22]. PID systems provide control through 3 main factors called K_p,K_i and K_d. These systems are formed by multiplying error by proportional, integral and derivative coefficients [23]. By changing the control coefficients, the controller response specifications such as overshoot, steady state error, settling time and rise time can be observed. Also, the PID controllers are easy to carry out, that is why they are generally used. The coefficients must be optimized for getting better results in these systems.

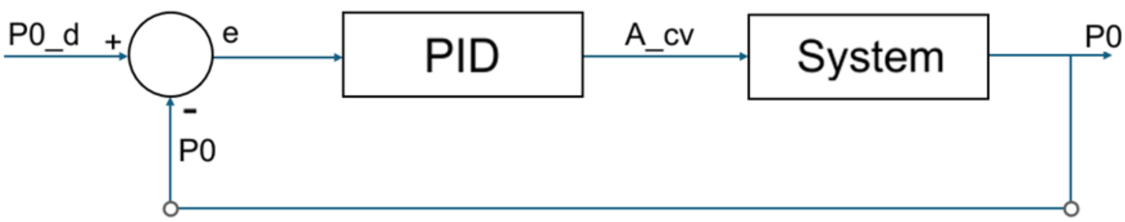

Figure 2. PID control of the stagnation pressure supersonic blowdown wind tunnel

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In the literature, there are mainly two controlled parameters as stagnation pressure and valve mass flow rate. In this study, the stagnation pressure is controlled as given in Figure 2.

4. Optimization

Optimization methods use mathematical algorithms to maximize system performance or minimize errors. There are many optimization methods in the literature, and they can be divided into two categories: classical and meta-heuristic. Gradient Descent (GD), a traditional optimization method, uses derivative (gradient) information to find the minimum point of cost function. The derivative of a function indicates the slope (direction) of the function at that point. If the slope is positive, the algorithm moves backwards (in the negative direction) to reach smaller values; if the slope is negative, it moves forward (in the positive direction). With this movement, it is tried to reach the minimum value [24].

4.1. Artificial bee colony algorithm

The form of knowledge that results from the actions of individuals without a centralized decision-making body is called swarm intelligence. Organisms such as ants, bees, swarms of birds, schools of fish, etc., act with swarm intelligence [14, 25]. These swarms are driven by a common goal (food selection, self-preservation, finding energy). Various artificial intelligence algorithms have been developed inspired by the behavior of swarms. Artificial intelligence bee colony, one of these artificial intelligence algorithms, was first discussed by Karaboğa in 2005 [25]. The artificial intelligence bee colony algorithm is modelled based on the food selection and dance movements of bees and the model consists of three main components: food source, employed foragers and unemployed foragers. The quality of a food source depends on many factors, such as the distance of the food from the nest, the diversity or density of the food, and the ease of access to the food. Employed foragers are associated with a specific resource and carry information about this resource (direction and distance from the nest) to the hive. There are two types of unemployed foragers, scouts and explorers. Unemployed foragers do not have specific resources like labor foragers, so they are constantly looking for food sources. Scout bees look for new food sources around the hive to increase food diversity. Onlooker bees stay in the nest and forage with information from worker foragers. The dance part is very important in the communication between bees. During the dance the bees learn about the quality of the food [26].

Each food around the hive is a possible solution. The ABC algorithm starts with a randomly assigned bee. One bee is assigned for each food source, so that as many bees work as there are food sources. The number of Honeybees (nHB) is the parameter that defines the size of the colony. The ABC algorithm starts with explorer bees finding food sources. The worker bees go to the food sources found by the explorer bees and the food quality is assessed by the scout bees. The worker bee whose food source is exhausted becomes a scout bee. This cycle continues until the best quality food source is found [26].

4.1.1. Employing bees and generating new solutions

Recruited bees randomly move towards other sources and try to find better food sources. The food source is expressed as a permutation and the mathematical model is constructed as follows. This ensures diversity and makes the algorithm's solution space more comprehensive.

$$stepsize = rand_{(i)(j)}.(HB - HB[permute(i)(j)])$$

$$newHB = HB + stepsize \tag{8}$$

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□□□□$_{(□)(□)}$ [-1 1] is a number randomly selected from the range. i is the number of honeybees, and j is the number of dimensions of the problem [26].

4.1.2. Onlooker bees and exploitation process

The solutions discovered by employed bees are shared with onlooker bees, who then evaluate them based on a selection probability. Onlooker bees focus on improving specific solutions by exploiting their neighborhood. The selection process is typically conducted, where higher-quality solutions are given priority for further improvement.

$$P_{(i)} = \frac{PFit_{(i)}}{\sum_{i=1}^{nHB} PFit_{(i)}} \tag{9}$$

$PFit_{(i)}$ is the penalised objective function value of the first food source [26].

$$stepsize = rand_{(i)(j)}.(HB_{rws} - HB[permute(i)(j)])$$

$$newHB = \begin{Bmatrix} HB_{rws} + stepsize, & if\ rand < mr \\ HB_{rws,} & otherwise \end{Bmatrix} \tag{10}$$

4.1.3. Scout bees and ensuring diversity

If a solution cannot be improved after a certain number of iterations, it is abandoned, and scout bees are activated. Scout bees generate entirely new random solutions in the search space. This phase introduces diversity and helps the algorithm escape from local optima. By replacing abandoned solutions, scout bees contribute to the overall performance of the algorithm [26].

4.2. Objective functions

Objective functions are used for the optimization of PID parameters. In this study, there are three types of objective functions. These are Integral Absolute Error (IAE), Integral Squared Error (ISE) and Integral Time-weighted Absolute Error (ITAE).

Table 1. Objective functions

Objective Function	Mathematical Formula
Integral of Absolute Error (IAE)	$\int_0^t \lvert e(t)\rvert dt$
Integral of Squared Error (ISE)	$\int_0^t e(t)^2 dt$
Integral of Time-weighted Absolute Error (ITAE)	$\int_0^t t\lvert e(t)\rvert dt$

In this paper, PID coefficients are obtained by using GD and ABC with objective functions those are ISE, IAE, ITAE. The graph of the control system was obtained with the PID coefficients. By comparing the graphs obtained, the optimum PID coefficients for the control system were determined. The objective function formulations used are given in Table 1.

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5. Results and Discussion

The gradient descent and ABC algorithms simulation results have been examined for a SBWT. The ABC algorithms are tested for three cost functions: ISE, IAE, and ITAE. In this study, 20 honeybees are used, the maximum number of objective function evaluations (maxNFEs) is chosen as 400, and the modification rate (mr) is chosen as 0.8. The optimizations are implemented several times to find the best results. The coefficients obtained as the result of optimizations are given in Table 2. Optimizations were performed for the case where the Mach value is 2 and the stagnation pressure is $0.25 * 10^6\ Pa$.

Table 2. PID coefficients

Optimization Methods	K_p	K_i	K_d
Gradient Descent	$1.6012 * 10^{-5}$	$1.2402 * 10^{-5}$	$-1.6832 * 10^{-7}$
ABC (ISE)	$8.8251 * 10^{-5}$	0	0
ABC (IAE)	$4.8067 * 10^{-4}$	$1.5718 * 10^{-5}$	$2.4207 * 10^{-7}$
ABC (ITAE)	$4.2337 * 10^{-4}$	$1 * 10^{-4}$	0

The optimized PID coefficients are implemented in the SBWT. The PID results are shown in Figure 3, and control signals in Figure 4. The results show that all the controllers run regularly for nearly 46.5-47.5 seconds. This small interval is important for controllers, as this system consumes the air stored in the tank. Therefore, there is a very short run time for each tunnel test.

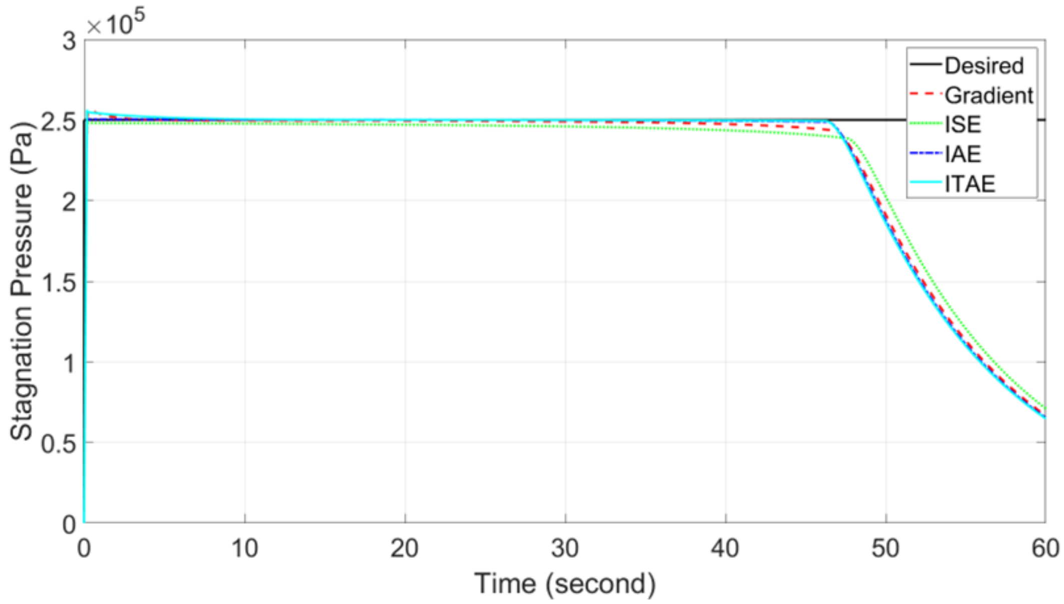

Figure 3. Optimized PID results

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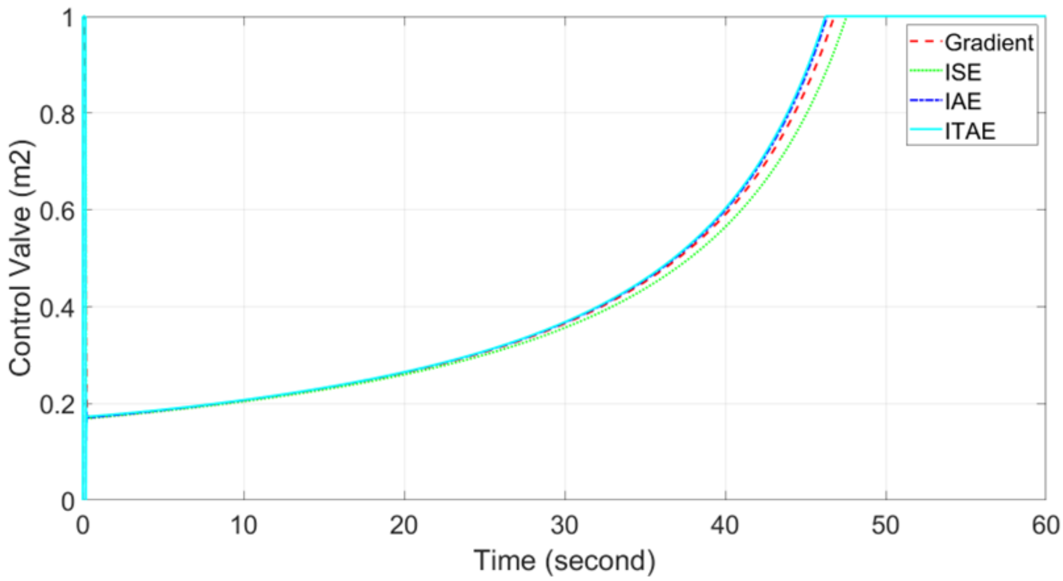

Figure 4. Optimized PID control signals

When the wind tunnel starts working, the control valve must be opened to its limit immediately as seen in Figure 4. Thus, the stagnation pressure reaches the desired values quickly. The PID control coefficients must provide this condition. As seen from the results, the four control signals provide a fast reaction but the ITAE cost function and GD methods have overshoots. The others (ISE and IAE) do not have overshoot values.

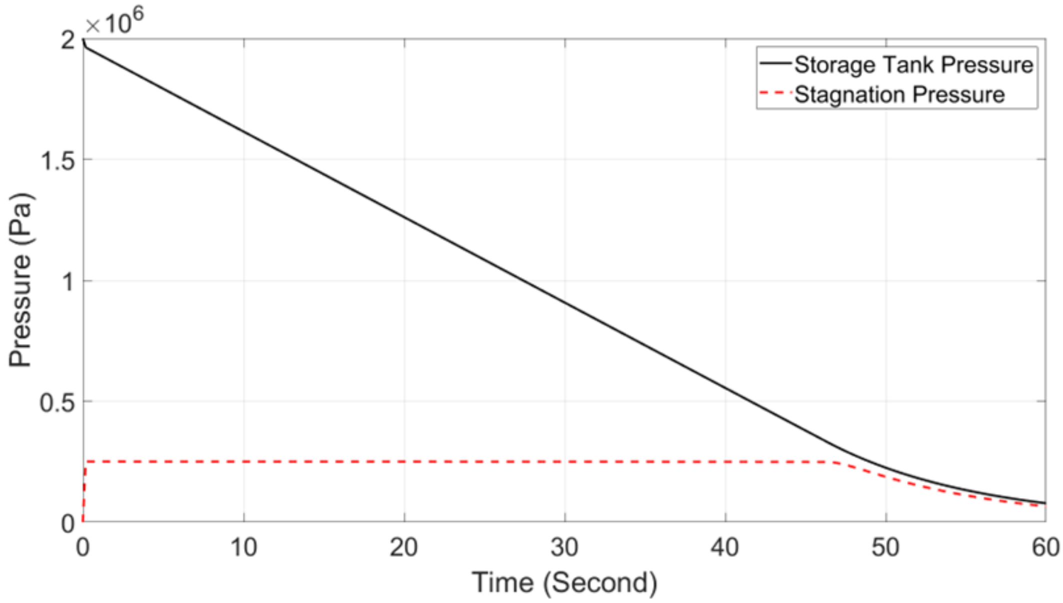

Figure 5. Storage tank and stagnation pressure relation for IAE optimized PID control

After the control valve is quickly opened to the end, it closes a little and opens slowly to keep the pressure at the desired level. Because in the meantime, the storage tank pressure declines with time. For this reason, as the storage tank pressure decreases, the control valve should be opened larger to ensure that the stagnation pressure is at the desired level. The relationship between the storage tank and stagnation pressure can be seen in Figure 5, which is the result of PID optimized with IAE cost function.

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When the results in Table 3 are examined, it is seen that the ISE and IAE optimized PID have better performance compared to the others in terms of overshoot and settling time. However, the ISE-optimized PID never reaches the desired pressure, and this causes a high Root Mean Squared Error (RMSE) value. This is an undesirable situation in tunnel tests.

The RMSE values are calculated for 46 seconds. Because after the 46^{th} second, the storage tank pressure can no longer provide the flow required for the desired stagnation pressure.

Table 3. Comparison of control performances

Methods	Overshoot (%)	Settling Time (s)	RMSE (46s)
Gradient Descent	2.50	0.623	$9.2238 * 10^3$
ABC (ISE)	0	0.178	$9.9525 * 10^3$
ABC (IAE)	0	0.178	$8.9664 * 10^3$
ABC (ITAE)	2.51	0.2	$9.0202 * 10^3$

As seen from Table 3, the PID optimized by IAE is not only overshoot-free but also has the minimum settling time and the minimum RMSE. So, it has the best control performance compared to others.

6. Conclusion

A modeling of an SBWT was conducted that addresses the challenges of achieving stable and precise control of stagnation pressure during the short and critical operation times. Considering the highly nonlinear nature of the SBWT system, the determination of the PID coefficients poses a great challenge. To overcome this, a metaheuristic optimization approach based on the Artificial Bee Colony (ABC) algorithm is implemented to determine PID coefficients that minimize the steady state error on the desired pressure value and provide maximum test time.

The PID controller coefficients are optimized using three different objective functions: Integral of Absolute Error (IAE), Integral of Squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE). These methods are compared to the Gradient Descent method.

In conclusion, it was found that the optimization with the IAE (Integral Absolute Error) objective function gives the best performance. The IAE-optimized PID controller achieved zero overshoot, the shortest settling time, and the lowest RMSE, thus maximizing the efficiency of the limited test time by ensuring rapid and stable pressure regulation. In contrast, the ISE-optimized PID controller failed to maintain the desired stagnation pressure, and both Gradient Descent and ITAE-optimized PID controllers exhibited undesirable overshoots.

The findings of this work underline the potential of the ABC algorithm with the IAE objective function, as a highly effective strategy for PID optimization for complex systems. So, this approach is planned to be tested in the real environment and with different systems in future studies.

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Authorship contribution statement
Kıymet Nihal Nur Taş, *Artificial Bee Colony Design, Revision and Writing.* **Sultan Dinçsoy,** *Literature Research, Revision and Writing.* **Levent Can,** *PID Design, Revision and Writing.* **Berna Tuğbay,** *Supersonic Tunnel Model Design, Revision and Writing.* **Hasan Tabanlı,** *Revision and Improvement of the Text, Supervision.* **Muhammet Öztürk,** *Software, Revision and Writing, Supervision.*

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