An Approach of Optimising S-curve Trajectory for a Better Energy Consumption..

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***Abstract*—In today's manufacturing industry, higher productivity and sustainability should go hand-in-hand. This practice is induced by governmental regulations as well as customers' awareness. For the current time, an inexpensive solution is motion planning for an improved energy consumption. This paper introduces a general approach that is valid for testing and optimising energy consumption of a certain motion profile. Being commonly used, s-curve motion profile is reconstructed and optimised for a better energy consumption. The Particle Swarm Optimisation method (PSO) is used because of its mathematical simplicity and quick convergence. The results show potential energy reduction and better positioning for the system configured according to the optimised s-curve.**

I. Introduction

Energy consumption in industry has always been an area of intensive research, and is getting more attention with the increased concern of resources saving, high energy prices, customers' interaction and environmental regulations. In Europe, manufacturing is considered as a major contributor to the electrical energy consumption and oil intake [1]. Similarly, the energy consumption of China's manufacturing industry accounted for 57.4% of the total energy consumption in 2014 [2]. A recent observation of the energy consumption in UK revealed that industry consumes 17% of the total energy [3].

At the shop floor level, automated reconfigurable equipment such as robots and CNC machines occupies a huge proportion of the total machinery and contributes remarkably to the total energy consumption. For example, 70% of the electricity consumed in German industry is used in operating electric drives [4]. Currently, the ultimate solution of minimising the amount of energy such equipment consumes is by using motion design techniques. In this context, motion planning is regarded as an inexpensive and effective method that doesn't require modifying or redesigning the physical system [5] .

Many motion profiles were introduced using the mathematical continuity as a measure of their smoothness. In parallel, different optimisation techniques were used for the purpose of limiting the jerk or the maximum acceleration. However, the selection of the motion profile is strongly linked to the controller and actuator specifications especially the actuator's maximum speed and maximum acceleration. As a result, trapezoidal velocity and s-curve motion profiles are still popular choices in industrial practice. Additionally, making use of the maximum velocity and acceleration limits can shorten the cycle time and enhance productivity. This might be satisfy the producer but it is questionable how economically viable the chosen motion profile is in terms of energy consumption. From a technical point of view, energy criteria based trajectory planning enhances the accuracy of tracking and decreases the stress on the machine's mechanical structure [6].

Extensive work has been done in the field of motion planning for the purpose of energy consumption reduction applied to robotics and CNC machines. An approach of linking minimum jerk and energy consumption was introduced in [7]. For balancing energy consumption with the cycle, the authors in [8] formulated a weighted cost function to be solved by means of the Environment-Gene evolutionary Immune Clonal Algorithm (EGICA). The real-coded genetic algorithm was used in [9] to generate a point-to-point PTP trajectory of high degree polynomials for optimal energy consumption. In [10], [11], convex optimisation techniques were used for tuning the trapezoidal velocity profile parameters so that it achieves the minimum energy consumption. Recently, it has been confirmed by [12] that energy consumption in robotics can be reduced by using polynomials instead of trapezoidal velocity profiles. According to [13], the commonly used optimisation criteria can be:

- The productivity expressed in minimum cycle time.
- The quality and accuracy in terms of minimum jerk.
- The minimum energy consumption.
- Hybrid criteria, e.g. minimum time and energy.

However, a general approach of testing motion profile energy performance is still needed. In this paper, a mathematical model is used to assess the potential of energy consumption reduction of the desired motion profile in the point-to-point (PTP) motion. Due to its popularity, s-curve will be used for motion planning. For a good trade-off between productivity and sustainability, an optimisation process, whose cost function is the energy consumed, is performed under the constraints of maximum velocity, maximum acceleration and maximum cycle time.

The remainder of this paper is as follows: section II discusses the physical and mathematical modelling of a mechanical system; in section III, an overview of the Particle Swarm Optimisation and its implementation is presented; the results and discussion are provided in section IV; and finally section

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V concludes the paper.

II. Modelling

A. The physical modelling

According to Biagiotti and Melchiorri [14], a single degree of freedom system composed of a mass m, a spring with stiffness coefficient k and a damper c can be represented as illustrated in Fig.1.

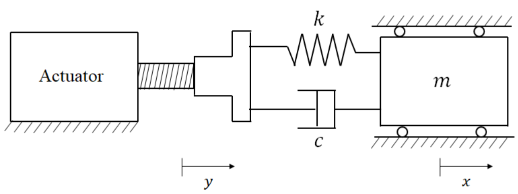

Fig. 1. Linear model with one degree of freedom [14]

Considering y the motion input (the reference trajectory) that is the s-curve as mentioned earlier, and x the motion output, it will clarified how to design the input and obtain the output in order to find the energy consumed and minimise it later.

B. The input design (reference trajectory)

The trajectory is composed of seven time segments as illustrated in Fig.2.

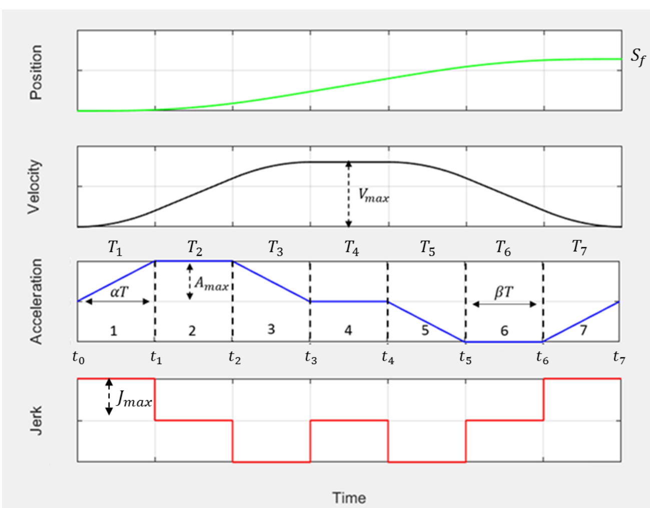

Fig. 2. The s-curve trajectory

With t referring to time and considering the initial time t_0 and initial position s_0 zero, the equation of the acceleration $a(t)$ is written as follows:

$$a(t) = \begin{cases} m_1 t + b_1 & t \in [0, t_1] \\ A_{max} & t \in [t_1, t_2] \\ m_3 t + b_3 & t \in [t_2, t_3] \\ 0 & t \in [t_3, t_4] \\ m_5 t + b_5 & t \in [t_4, t_5] \\ -A_{max} & t \in [t_5, t_6] \\ m_7 t + b_7 & t \in [t_6, t_7] \end{cases} \quad (1)$$

where m_n stands for the straight line slope in the time interval n , and b_n is the initial value of the acceleration in the time interval n. The velocity and position equations are found by integration and adding the constants that preserve the mathematical continuity. By integrating twice to get the velocity $v(t)$ and the position $s(t)$ we observe:

$$v(t) = \begin{cases} \frac{m_1}{2} t^2 + b_1 t + c_{1v} & t \in [0, t_1] \\ A_{max} t + c_{2v} & t \in [t_1, t_2] \\ \frac{m_3}{2} t^2 + b_3 t + c_{3v} & t \in [t_2, t_3] \\ c_{4v} & t \in [t_3, t_4] \\ \frac{m_5}{2} t^2 + b_5 t + +c_{5v} & t \in [t_4, t_5] \\ -A_{max} t + +c_{6v} & t \in [t_5, t_6] \\ \frac{m_7}{2} t^2 + b_7 t + c_{7v} & t \in [t_6, t_7] \end{cases} \quad (2)$$

$$s(t) = \begin{cases} \frac{m_1}{6} t^3 + \frac{b_1}{2} t^2 + c_{1v} t + c_{1s} & t \in [0, t_1] \\ \frac{A_{max}}{2} t^2 + c_{2v} t + c_{2s} & t \in [t_1, t_2] \\ \frac{m_3}{6} t^3 + \frac{b_3}{2} t^2 + c_{3v} t + c_{3s} & t \in [t_2, t_3] \\ c_{4v} t + c_{4s} & t \in [t_3, t_4] \\ \frac{m_5}{6} t^3 + \frac{b_5}{2} t^2 + +c_{5v} t + c_{5s} & t \in [t_4, t_5] \\ -\frac{A_{max}}{2} t^2 + +c_{6v} t + c_{6s} & t \in [t_5, t_6] \\ \frac{m_7}{6} t^3 + \frac{b_7}{2} t^2 + c_{7v} t + c_{7s} & t \in [t_6, t_7] \end{cases} \quad (3)$$

c_{nv} represents the velocity integration constant in the time interval n, and c_{ns} is the position integration constant in the time interval n.
By defining:

$$T_1 = T_3 = T_5 = T_7 = \alpha T; \qquad \alpha \in]0, 0.25[\quad (4)$$
$$T_2 = T_6 = \beta T; \qquad \beta \in]0, 0.5[\quad (5)$$
$$T_4 = T - (4\alpha T + 2\beta T); \qquad 4\alpha + 2\beta < 1 \quad (6)$$

The calculation of the constants' values yields:
$b_1 = 0$
$b_3 = A_{max}(\beta + 2\alpha)/\alpha$
$b_5 = -A_{max}(\beta + 2\alpha - 1)/\alpha$
$b_7 = -A_{max}/\alpha$
$c_{1v} = 0$
$c_{2v} = -TA_{max}\alpha/2$
$c_{3v} = -TA_{max}(\beta^2 + 2\alpha\beta + 2\alpha^2)/(2\alpha)$
$c_{4v} = TA_{max}(\alpha + \beta)$
$c_{5v} = -TA_{max}(\beta^2 + 2\alpha\beta - 2\beta + 2\alpha^2 - 4\alpha + 1)/(2\alpha)$
$c_{6v} = -TA_{max}(\alpha - 2)/2$
$c_{7v} = TA_{max}/(2\alpha)$
$c_{1s} = 0$
$c_{2s} = T^2 A_{max}\alpha^2/6$
$c_{3s} = T^2 A_{max}(\beta^3 + 3\alpha^2\beta + 3\beta^2\alpha + 2\alpha^3)/(6\alpha)$
$c_{4s} = -T^2 A_{max}(\beta^2 + 3\alpha\beta + 2\alpha^2)/2$
$c_{5s} = -T^2 A_{max}(\beta^3 + 9\alpha\beta^2 - 3\beta^2 + 21\alpha^2\beta - 12\alpha\beta + 3\beta + 14\alpha^3 - 12\alpha^2 + 6\alpha - 1)/(6\alpha)$
$c_{6s} = -T^2 A_{max}(6\beta^2 + 18\alpha\beta - 6\beta + 12\alpha^2 - 9\alpha + 3)/6$
$c_{7s} = -T^2 A_{max}(6\alpha\beta^2 + 18\alpha^2\beta - 6\alpha\beta + 12\alpha^3 - 6\alpha^2 + 1)/(6\alpha)$
It can be found that the reference final position S_f, the

maximum acceleration A_{max}, the maximum velocity V_{max} and the maximum jerk J_{max} are:

$$S_f = T^2 A_{max}(\alpha + \beta)(1 - 2\alpha - \beta) \quad (7)$$

$$A_{max} = \frac{S_f}{T^2(\alpha + \beta)(1 - 2\alpha - \beta)} \quad (8)$$

$$V_{max} = \frac{S_f}{T(1 - 2\alpha - \beta)} \quad (9)$$

$$J_{max} = \alpha T \quad (10)$$

Therefore, the reference final position can be expressed in terms of the maximum values of velocity, acceleration and jerk:

$$S_f = \frac{V_{max}(J_{max}TA_{max} - A_{max}^2 - J_{max}V_{max})}{A_{max}J_{max}} \quad (11)$$

C. The output

The dynamics of the system in Fig.1. is described as:

$$m\ddot{x} + c\dot{x} + kx = c\dot{y} + ky \quad (12)$$

$$\ddot{x} + 2\xi\omega_n\dot{x} + kx = 2\xi\omega_n\dot{y} + \omega_n^2 y \quad (13)$$

where ξ and ω_n are the natural frequency and the damping ratio respectively.

$$\omega_n = \sqrt{\frac{k}{m}}; \quad \xi = \frac{c}{2m\omega_n}$$

An abstract algebraic solution is not easy to find with an input that is not sinusoidal (i.e. the right sides of equations (12 &13) are not harmonic). One solution is to replace them by their Fourier series expansions. Then the equation (13) becomes:

$$\ddot{x} + 2\xi\omega_n\dot{x} + kx = \frac{a_0}{2} + \sum_{j=1}^{\infty} a_j \cos(j\omega t) + b_j \sin(j\omega t) \quad (14)$$

where a_0, a_j and b_j are Fourier coefficients and $j = 1, 2, 3...$ The last equation has a particular solution x_p that is the summation of three particular solutions x_{1p}, x_{2p} and x_{3p}:

$$x_{1p}(t) = \frac{a_0}{2\omega_n^2} \quad (15)$$

$$x_{2p}(t) = \sum_{j=1}^{\infty} \frac{a_j}{\omega_n^2\sqrt{(1 - j^2r^2)^2 + (2\xi jr)^2}} \cos(j\omega t - \phi_j) \quad (16)$$

$$x_{3p}(t) = \sum_{j=1}^{\infty} \frac{b_j}{\omega_n^2\sqrt{(1 - j^2r^2)^2 + (2\xi jr)^2}} \sin(j\omega t - \phi_j) \quad (17)$$

where:

$$\phi_j = \tan^{-1}(\frac{2\xi jr}{1 - j^2r^2}); \quad r = \frac{\omega}{\omega_n}$$

According to [15], the few first four or five harmonics of the series are sufficient for good solution accuracy.

Another solution is to use Matlab/Simulink mathematical model that is equivalent to the physical model (Fig.3.). It provides a quick and practical solution in Matlab environment that is popular among engineers.

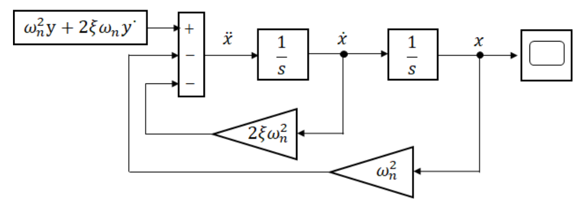

Fig. 3. Simulink mathematical model of the physical system

D. The energy consumption

For the proposed system, when the mass moves from the initial position x_0 to the final position x_f the equations of the kinetic energy (KE) and the potential energy (PE) stored in the spring and the energy dissipated by the damper (DE) are respectively as follows:

$$KE = \frac{m}{2}(\dot{x_f}^2 - \dot{x_0}^2) \quad (18)$$

$$PE = \frac{k}{2}(x_f^2 - x_0^2) \quad (19)$$

$$DE = \frac{c}{2}\int_{t_0}^{T} \dot{x}dt \quad (20)$$

Then the total consumed energy E becomes:

$$E = KE + PE + DE \quad (21)$$

III. Optimisation

The Particle Swarm Optimisation (PSO) is a biologically inspired algorithm that was introduced by Kennedy and Eberhart in 1995 [16]. It depends on a population of particles each of which has its own position x and its personal best $(xbest)$. At the same time, each particle moves towards the global best $(xgbest)$ in a specific velocity (Fig.4.). Based on this, the equations that rule particles movement are [17]:

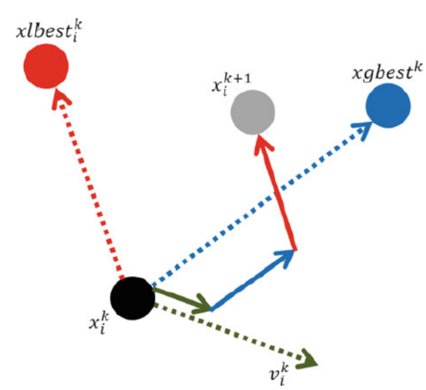

Fig. 4. A schematic movement of a particle [17]

$$v_{i,j}^{k+1} = v_{I,j}^{k+1} + c_1r_1(xbest_{i,j}^k - x_{i,j}^k) + c_2r_2(xgbest_i^k - x_{i,j}^k) \quad (22)$$

$$x_{i,j}^{k+1} = x_{i,j}^k + v_{i,j}^{k+1} \quad (23)$$

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Note that the velocity and position of the particles are different from the motion velocity and position. Similarly, the symbols i, j and k in this section are related only to the particles.
$x_{i,j}^{k+1}, v_{i,j}^{k}$ are the jth component of the ith particle position and velocity vector, respectively, in the kth iteration. r_1, r_2 are two random numbers in the range [0,1] obtained using the Normal Distribution. c_1, c_2 represent the particle's personal cognition and its social behaviour respectively. An inertia term w was added to equation (22) to balance the local and global search tendencies of the particles.

$$v_{i,j}^{k+1} = wv_{I,j}^{k+1} + c_1 r_1 (xbest_{i,j}^{k} - x_{i,j}^{k}) + c_2 r_2 (xgbest_{i}^{k} - x_{i,j}^{k}) \quad (24)$$

Later on, PSO was modified by Clerc [18] by adding the constriction coefficient which improves the convergence of the PSO, and thus the velocity vector formula becomes:

$$v_{i,j}^{k+1} = \chi[wv_{I,j}^{k+1} + c_1 r_1 (xbest_{i,j}^{k} - x_{i,j}^{k}) + c_2 r_2 (xgbest_{i}^{k} - x_{i,j}^{k})] \quad (25)$$

$$\chi = \frac{2}{|(2 - \phi - \sqrt{\phi^2 - 4\phi})|}; \ \phi = c_1 + c_2, \phi > 4$$

A. *Problem Formulation*

The Particle Swarm Optimisation (PSO) was chosen for optimising the energy consumption due to the following reasons [19] [20]:

- The ability of being used in multi-dimension, discontinuous and nonlinear problems.
- Low computational cost.
- Its underlying concepts are simple and easy to code.
- The number of parameters to adjust is fewer compared to other methods.
- It remembers the good solutions resulting from previous iterations.
- The fast convergence of the objective function.
- The final solution is not highly affected by the initial population.

For the proposed problem of minimising the energy consumption by designing the proper s-curve trajectory, each particle of the population is assigned a position that is a horizontal vector of $[\alpha, \beta, T]$. The interaction of the vector components generates corresponding values of the constraints and the cost function (minimum energy). After that the particles' movement towards the cost function is ruled by the equations (23, 25) introduced above. The problem is formulated as follows:

$$\begin{aligned} &Minimise\ E = KE + DE + PE \quad (26) \\ &subjected\ to: T < T_{lim} \\ &A_{max} < A_{lim} \\ &V_{max} < V_{lim} \\ &where\ T > 0,\ A_{max} > 0, V_{max} > 0 \end{aligned}$$

T_{lim} is the maximum allowed cycle time, and A_{lim}, V_{lim} are the motor's motion constraints.

IV. Results and Discussion

For the proof of the proposed concept, some simulation examples are introduced. The design data include the maximum allowed cycle time (T_{lim}), the reference final position (S_f) and the actuator limits (maximum velocity ($V_{lim} = 0.2$ m/sec) and maximum acceleration ($A_{lim} = 3$ m/sec^2)). In the simulations, a mechanical flexible system whose natural frequency $\omega_n = 60$ rad/sec and dumping coefficient $\xi = 0.1$ is considered. The followed approach is illustrated in Fig.5., and is valid for any motion profile.

When applying the constraints as they are in equation (26),

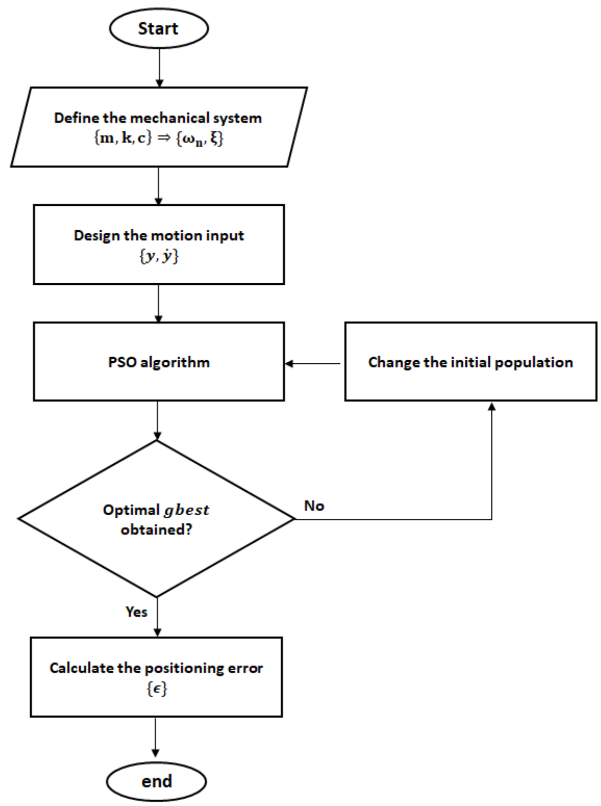

Fig. 5. The approach of finding optimal energy consumption

a remarkable residual vibration is produced (Fig.6.). To limit such an effect, another constraint, the jerk limit J_{lim} has to be added.

$$0 < J_{max} < J_{lim}; J_{lim} = 40 \text{ m/sec}^3$$

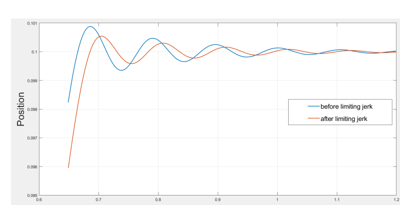

Fig. 6. The residual vibration before and after limiting the jerk

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The results are shown in Table I. The energy values in the column labelled E_{opt} refer to the optimised energy values. E_{TrVel} refers to the energy consumed using the trapezoidal velocity motion profile under the same conditions optimal energy values calculated at. T_{opt} is the optimal cycle time corresponding to E_{opt}. It can be noted that there is a potential of reducing the energy using the proposed approach. Further reduction can be achieved without limiting the jerk, but in this case more residual vibrations are induced.

TABLE I
THE ENERGY CONSUMPTION FOR MANY TASKS

Task	S_f(m)	T_{lim}(sec)	E_{TrVel}(J)	T_{opt}(sec)	E_{opt} (J)
1	0.1	0.75	16.9827	0.7237	16.5226
3	0.12	1	24.6752	0.9295	24.1166
2	0.15	1.1	38.9828	1.0548	38.2938
4	0.2	1.4	70.0368	1.2266	69.1669
5	0.24	1.8	101.2292	1.6291	100.1615

The issue of accurate positioning is of high importance in many applications. Therefore, the positioning error ϵ was calculated for each task and presented in Table II.

$$\epsilon = S_f - x_f$$

TABLE II
THE POSITIONING ERROR FOR MANY TASKS

Task	S_f(m)	T_{lim}(sec)	ϵ (m)
1	0.1	0.75	1.66e-04
3	0.12	1	9.25e-05
2	0.15	1.1	1.31e-04
4	0.2	1.4	1.83e-04
5	0.24	1.8	1.44e-04

In fact, the residual vibrations affect remarkably the accurate positioning and at the same time a minimum energy consumption helps eliminate the positioning error. For example, in [11], having potential and kinetic energies that are equal to zero at the end of motion was considered a condition of having zero residual vibration.

Despite its simplicity compared to other optimisation algorithms, PSO parameters such as the constriction coefficient, the particle's personal cognition and its social behaviour need 'tuning' depending on the systems parameters. Fig.7. and Fig.8. describe the evolution of the conversion of the cost function (energy) and its constraints respectively for Task No.4.

In relation to this, [20] indicates that the swarm size must be increased for multidimensional problems. Moreover, the initialisation technique and the maximum velocity of the particles movement affect remarkably the final solution. For the proposed problem, a multi-pooling technique mixed with using variable maximum speeds of the particles was employed in order to increase the availability of random solutions. Nevertheless, a special concern should be given to the other parameters.

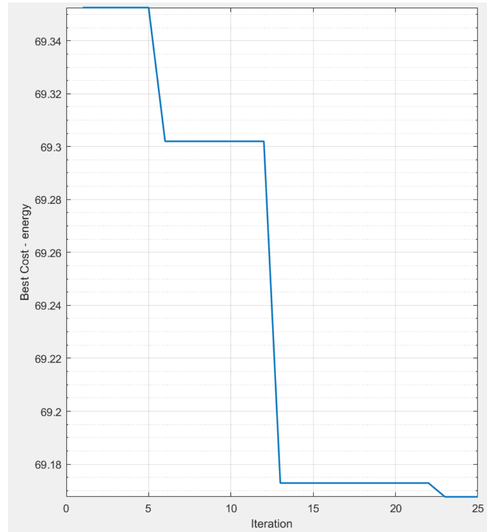

Fig. 7. The conversion of the PSO

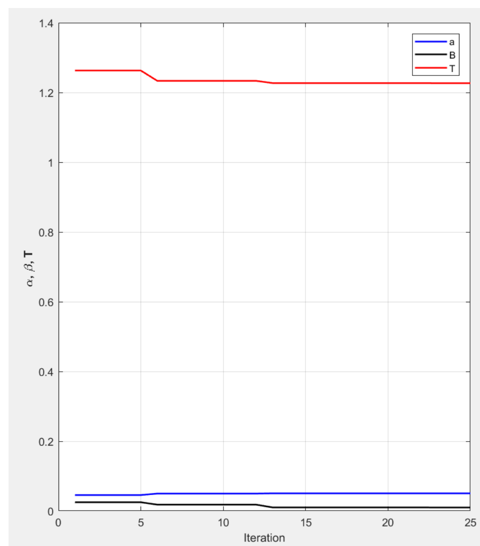

Fig. 8. The evolution of PSO parameters

V. CONCLUSION

In this paper, a general approach of estimating the energy consumption when actuating a mechanical system with a predefined trajectory is introduced. The proposed approach targets optimising the input (the reference trajectory) to obtain an output that is satisfactory from the perspectives of productivity and sustainability and can be extended to eliminate the residual vibrations. To prove its efficiency, the approach was applied on s-curve after being reformulated.

Future work includes developing the approach by tuning the optimisation parameters or using another optimisation algorithm, supporting the simulation with experimental results and testing other motion profiles with different initial conditions.

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