Design of an Electric Elevator Drive with High Riding Quality under Jerk Control

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ABSTRACT

Sudden movements during the start and stop of electric elevators, known as jerks, can cause discomfort for passengers and negatively affect the performance and lifespan of their mechanical and electrical subsystems. Modern drives cannot directly regulate jerk, necessitating the development of methods to mitigate its effects. This study focuses on designing optimal S-curve motion profiles to reduce jerk in elevator systems driven by an induction motor. The motor operates according to these profiles when integrated with a TMS320F28335 Digital Signal Processor (DSP) under Direct Torque Control (DTC). Precise motor control is achieved using an incremental rotary encoder, current sensors, and voltage sensors, while an accelerometer sensor connected to an Arduino Nano measures the jerk. This comprehensive approach ensures precise regulation, smooth performance, and minimal sudden changes in acceleration, highlighting the effectiveness of DTC combined with S-curve profiles in enhancing elevator system performance. The results demonstrate that integrating S-curve profiles into the DTC algorithm significantly improves ride comfort by mitigating jerk during acceleration and deceleration phases by up to 57.2% compared to systems without S-curve integration.

Keywords-elevator; induction motor; direct torque control; jerk reduction; TMS320F28335; S-curve

I. INTRODUCTION

The rapid increase in electromechanical systems, especially elevators, has accelerated city building. Multistory structures need good vertical transit systems as cities get taller, and elevators are in line with this need. Every multistory structure needs an elevator to move people and things quickly. Traction elevators are the most common, using ropes and counterweights to move the car [1]. Hydraulic elevators use a hydraulic ram to raise and lower the car, commonly used in low-rise buildings due to their lower cost and simpler installation process [2]. Machine Room-Less (MRL) elevators eliminate the need for a dedicated machine room, integrating the machinery within the shaft itself, which saves space and is increasingly popular in modern buildings [3]. Pneumatic elevators operate using air pressure to move the car and are often used in residential applications due to their minimal footprint and ease of installation [4]. Freight elevators are designed to carry heavy loads and are equipped with robust construction and control systems to handle industrial environments [5].

As a key issue, the safety of high-speed elevators in high-rise buildings must be addressed [6]. These elevators often experience fluctuating stresses. These forces can cause significant vibrations. Vibrations can make passengers uncomfortable and harm the elevator's mechanical and electrical parts, reducing its lifespan. Controlling fast movements is critical to minimize these effects and make passengers feel more comfortable. The best way to solve this problem is to use contemporary drives, such as Variable Frequency Drives (VFDs) and advanced control methods. These drives control the speed and torque of the AC motor, changing the input voltage and frequency (V/f) at a constant level [7]. This functionality is needed for smooth elevator starts and stops to lower mechanical stress and prolong the system's life. Many studies have examined the sudden movement of elevators and the resulting jerk as they move between floors. In

[1], a DC motor drive was presented to improve the movement of a new elevator for medium-height buildings. A PID-controlled permanent magnet DC motor was used to move the cabin. This drive made the elevator more efficient, reduced sudden movements, and improved comfort.

In [8], rectangular and sinusoidal jerk patterns were proposed to provide a smooth speed profile for a comfortable ride without reducing travel time. Reducing steady-state induction motor losses improved lift system performance. In [9], the elevator kinematic parameters were compared over time using MATLAB velocity modeling. The purpose was to slow down the elevator car gently with S-curves. The bends in the S-curves have two arcs to facilitate changes in acceleration and deceleration, reducing vibrations and smoother transport between floors. In [10], an elevator system was proposed, using a double-sided Linear Switched Reluctance Motor (LSRM) controlled by a speed pattern dedicated to smooth and jerk-free movements. In [11], it was stated that Direct Torque Control (DTC) is an option for induction motor drivers. This study focused on the SVM-DTC method, suggesting that speed profiling enhances lift comfort. The study in [12] examined how accelerations affect a Hybrid III dummy equipped with three-axis accelerometers during emergency stops. This study tested a progressive safety gear known for its quick reaction time and short braking distance under simulated lift conditions with varying cabin loads. By measuring accelerations on the dummy's parts and using indexes like HIC and Nij, this study assessed how these forces might impact passenger health. This underscores the need to integrate advanced safety features with control innovations for optimal elevator performance and passenger safety. In [13], a novel approach was presented to reduce losses in induction motor-based lift systems. This method is needed to find an energy-efficient motion pattern. The differential equation for the goal function links the motor's overall power loss to its spinning speed. Speed and acceleration are limited to protect passengers. To determine the optimal path, an appropriate Hamiltonian function was constructed, and Pontryagin's minimum principle was used.

Due to the strong dynamic responsiveness of Permanent Magnet Synchronous Motors (PMSMs) and the elevator speed controller's restricted bandwidth, typical beginning jerk control systems increase starting energy when either rotor flux linkage or static friction deviates from prescribed values. In [14], a novel disturbance observer was proposed to solve these problems, which, instead of adjusting the torque/current at startup, briefly modified the stator flux link speed. In [15], the performance of a linear elevator was improved by controlling the speed of the motor fed from VFD. This drive used the best off-line *V/f* pattern for the perfect speed curve profile, resulting in an 88% reduction in jerk levels, a smooth start and stop of the elevator cab, and a consistent speed of travel throughout the elevator floors. Recent studies have also sought to improve safety measures for braking systems beyond elevator controls. In [16], the focus was on improving the brakes of the rescue winches used in high-altitude rescues. This study aimed to optimize brake design and settings to achieve smoother deceleration, reducing discomfort, especially for vulnerable groups such as seniors and children. By developing new calculation methods and conducting tests, braking speed was significantly improved while reducing braking forces by 67.75% compared to previous designs. This highlights the importance of upgrading braking mechanisms for safer and more comfortable operations during critical rescue missions.

Despite significant advances, existing studies on elevator systems exhibit several shortcomings. Many conventional control systems rely on basic microcontrollers or PLCs, which may not provide the computational capacity needed for advanced control algorithms. Additionally, traditional systems often use simple relay-based switching or transistor modules, lacking integrated protection and precise feedback mechanisms. Although some studies have explored the use of PID-controlled DC motors or sinusoidal jerk patterns, they do not adequately address the need for comprehensive real-time monitoring and adjustments. Furthermore, the implementation of S-curve profiles in many research efforts is limited, often resulting in insufficient mitigation of mechanical jerks and suboptimal ride comfort. These limitations highlight the need for more sophisticated and integrated control solutions to improve elevator performance and passenger comfort.

This study aims to implement a functional prototype of a three-story rope elevator. A three-phase induction motor is used to drive the elevator cabin. Motor speed is controlled by applying the DTC algorithm with TMS320F28335 Digital Signal Processors (DSPs) to ensure an ideal S-curve speed profile. The elevator has advanced control systems that use ultrasonic sensors and limit switches. This study focuses on designing and using S-curve motion profiles. Unlike linear profiles, the S-curve approach reduces unexpected speed and slow changes, eliminating mechanical jerks. This study employs the sinusoidal limited-jerk trajectory approach adopted by [17]. Elevators benefit from this strategy since it saves time and minimizes jerks. The proposed elevator system must possess this characteristic to faithfully replicate real elevators. This study has multiple objectives: (i) reduce mechanical jerks to improve passenger comfort, (ii) improve elevator reliability and efficiency with current motor speed control and microcontrollers, and (3) build a high-performance elevator prototype that performs like a real elevator and can be easily modified for future systems. This will enable commercial vertical transportation options that use similar technologies.

II. DIRECT TORQUE CONTROL

The DTC, as shown in Figure 1, controls the torque and speed of the three-phase AC motor. This alternative to Field-Oriented Control (FOC) was created by Isao Takahashi and Toshihiko Noguchi in the mid-1980s to simplify the control procedure while maintaining performance [18]. FOC needs coordinate transformations and sophisticated modulation techniques, but DTC directly controls motor variables by picking optimal voltage vectors based on the motor's immediate state. It continuously monitors the motor's stator flux and torque, compares them to reference values, and applies voltage vectors to reduce error. This method provides fast torque response and durable performance, making it ideal for torque and speed control applications. DTC's ability to directly adjust torque without computations simplifies implementation and reduces system complexity, making it popular in industrial applications [19].

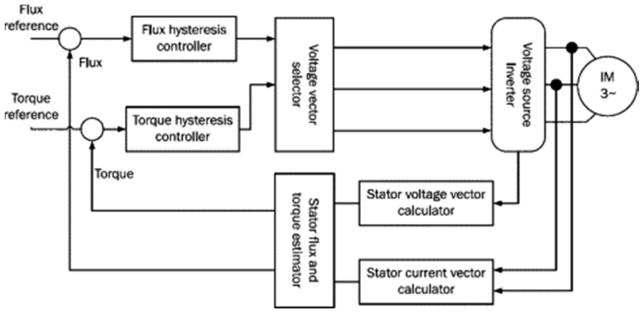

Fig. 1. Direct torque control.

III. JERK REDUCTION IN ELEVATORS

The most common elevator motion profiles are triangular and trapezoidal. In a trapezoidal motion profile, the system speed increases from zero to its maximum value, sustaining it for a predetermined duration (or distance), and then it decelerates to zero. However, the triangle motion profile accelerates to its maximum speed and then instantly decelerates to zero, maintaining a constant velocity. Unfortunately, none of these moving profiles is appropriate for motion systems, especially elevators, which must move smoothly, position properly, and remain stable after the move. Acceleration or deceleration causes jerks. Similar to velocity, jerk is acceleration's rate of change. Jerk gives a fast but uncomfortable jerky action. An abrupt acceleration change, or jerk, shakes industrial systems. Higher jerks cause more vibrations. Vibrations slow settling but diminish positioning accuracy. The jerky trapezoidal motion profile can be replaced by an S-curve motion profile in motion control systems [15]. An infinite jerk and rapid acceleration characterize a trapezoidal motion profile. To reduce jerk, acceleration, and deceleration transitions are flattened into an S-form.

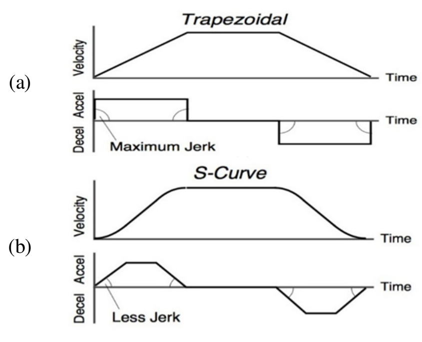

Fig. 2. Move profiles: (a) Trapezoidal, (b) S-curve.

IV. TRAJECTORY MOTION PROFILES

Acceleration must be constant and smooth so that the elevator system provides smooth electro-mechanical torque, lowering vibration and increasing longevity. Selecting the right jerk change form is necessary for smooth acceleration. In [17], a sinusoidal trajectory with limited jerk was proposed for FOC to enhance torque ripple, service life, and PMSM motion control. After open-loop system identification, an optimal H-infinity controller regulates the motor load velocity and position. The sinusoidal limited-jerk trajectory approach was improved to be compatible with elevator working mechanisms as one of the best solutions for time optimality and jerk continuity. Equation (1) ensures a limited jerk for the required velocity with a sinusoidal jerk waveform.

$$j = \begin{cases} j_m \sin\frac{2\pi}{T} t, & t \in [0, T] \\ 0, & t \in [T, t_2] \\ -j_m \sin\frac{2\pi}{T}(t - t_2), & t \in [t_2, t_3] \end{cases} \quad (1)$$

where t_3 is the overall period of cabin movement, the time T is taken for acceleration or deceleration, t_2 is equal to $t_3 - T$, which is the instant when the cabin begins deceleration, and j_m is the maximum jerk amplitude. Based on (1), the following relationships express the displacement d, acceleration a, and velocity v at certain intervals:

$$a = \int j\, dt + C_a \quad (2)$$

$$v = \int a\, dt + C_v \quad (3)$$

$$d = \int v\, dt + C_d \quad (4)$$

Initial conditions are used to establish constants C_a, C_v, and C_d. The formula for acceleration is derived from:

$$a = \cos\left(\frac{2\pi}{T} t\right) + C_a \quad (5)$$

C_a is calculated based on the premise that the acceleration is zero at $t = 0$:

$$C_a = \frac{j_m T}{2\pi} \quad (6)$$

During the interval $t\ [0,\ T]$, the acceleration expression is:

$$a = \frac{j_m T}{2\pi}\left(1 - cos\left(\frac{2\pi}{T} t\right)\right) \quad (7)$$

Constants for all other values are derived similarly, resulting in equations for acceleration, velocity, and displacement. Final acceleration, velocity, and distance profiles are:

$$a = \begin{cases} \frac{j_m T\left(1 - cos\left(\frac{2\pi}{T} t\right)\right)}{2\pi}, \\ a_m\ , \\ -\frac{j_m T\left(1 + cos\left(\frac{2\pi}{T}(t_2 - t)\right)\right)}{2\pi} \end{cases} \quad (8)$$

$$v = \begin{cases} \frac{j_m T\left(2\pi t - T\, sin\left(\frac{2\pi}{T} t\right)\right)}{4\pi^2} \\ \frac{j_m T^2}{2\pi} \\ \frac{j_m T}{2\pi}\left(T - \frac{\left(T\, sin\left(\frac{2\pi}{T}(t_2 - t)\right) + 2\pi(t - t_2)\right)}{2\pi}\right) \end{cases} \quad (9)$$

$$d = \begin{cases} \frac{j_m T}{4\pi}\left(t^2 - \frac{T^2\left(1 - cos\left(\frac{2\pi}{T} t\right)\right)}{2\pi^2}\right), & t \in [0, T] \\ \frac{j_m T^2}{4\pi}(2t - T), & t \in [T, t_2] \\ \frac{j_m T^2}{4\pi}\begin{bmatrix} (2t - T) - \frac{(t - t_2)^2}{T} \\ + \frac{T}{2\pi^2}\left[1 - cos\frac{2\pi}{T}(t - t_2)\right] \end{bmatrix}, & t \in [t_2, t_3] \end{cases} \quad (10)$$

At $t = t_3$, the maximum displacement value can be calculated as follows:

$$d_m = j_m \frac{T^2}{2\pi} t_2 \tag{11}$$

The maximum value of speed v_m can be found in the steady state by using the method described to find the speed v. The interval T can be calculated using the velocity magnitude equation as follows:

$$T = \sqrt{\frac{2\pi\, v_m}{j_m}} \tag{12}$$

Table I shows a list of symbols. Figure 3 shows the velocity profile of a sinusoidal trajectory. In the image, the proposed sinusoidal limited-jerk trajectory is used to illustrate how the end jerk, acceleration, and velocity values equal zero.

TABLE I. LIST OF SYMBOLS

Symbols	Description	Units
j_m	Maximum jerk	m/s^3
v_m	Maximum velocity	m/s
C_a	Acceleration constants	m/s^2
C_v	Velocity constants	m/s
C_d	Displacement constants	m
d_m	Maximum displacement	m
t_2	Deceleration moment	s
t_3	Total duration of movement	s
T	Acceleration/deceleration time	s

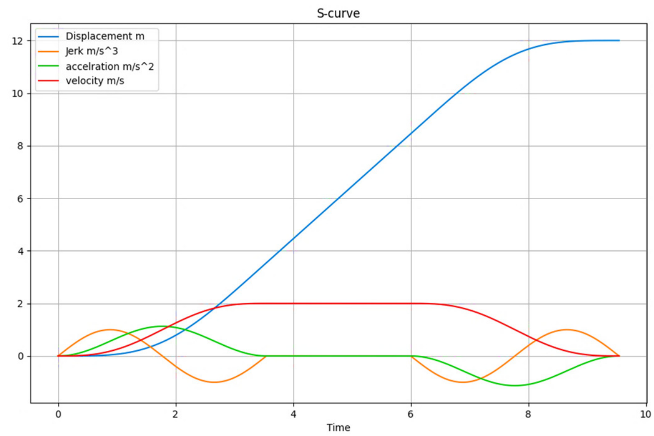

Fig. 3. Sinusoidal trajectory motion profiles.

V. EXPERIMENTAL WORK

As shown in Figure 4, an iron elevator system prototype was constructed with three floors, 200 cm high, 45 cm wide, and 55 cm deep. The 19×30 cm aluminum elevator cab was suspended by a rope that passed over two 7 cm diameter pulleys that are used to create a balanced and smooth vertical movement. The cabin could hold approximately 23.3 kg, including its weight. The cabin was driven by a 0.75 KW, 1395 rpm, 50 Hz delta-connected three-phase induction motor installed at the top of the elevator structure. The motor operated at a power factor of 0.75 and a line current of 2 A, producing 8 Nm torque. The pulleys efficiently elevated the cabin and things over the floors using the motor's torque. A braking mechanism ensured safe and speedy cabin stopping.

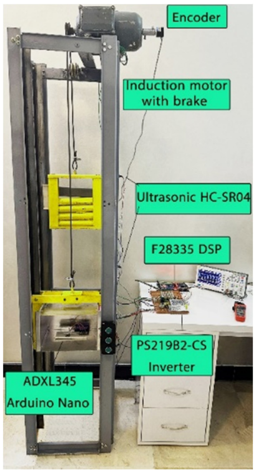

Fig. 4. Elevator system prototype.

The elevator movement was controlled through the control circuit shown in Figure 5. The circuit had a PS219B2-CS three-phase inverter module used as a low-power motor control. This module used IGBTs, free-wheeling diodes, and a driver circuit for strong performance and compactness. Motor control systems are more reliable and safer with overcurrent, short-circuit, under voltage, and overtemperature protection. The drive circuit also had a TMS320F28335 DSP with a 150 MHz high clock frequency, 12 high-speed Analog-to-Digital Converters (ADCs), and 16 Pulse Width Modulation (PWM) channels. The DSP code was developed and tested in Code Composer Studio (CCS). To apply DTC using the TMS320F28335 DSP, accurate measurement of voltage, current, position, and acceleration is crucial. Voltage sensors, such as the ZMPT101B, and current sensors, such as the ACS712, provide essential data, which the DSP samples through its ADCs for real-time processing. The voltage and current sensors were calibrated to provide accurate measurements by tuning the scale factor and offset. An incremental rotary encoder with 600 pulses per revolution connected to the DSP's Quadrature Encoder Pulse (QEP) module provided precise position feedback. The DSP generated 10 kHz PWM signals to control the motor efficiently, managing the elevator's movement.

To detect the position of the elevator car, HC-SR04 ultrasonic sensors were installed on each floor, ensuring accurate stopping and starting. An ADXL345 accelerometer sensor was used to detect the acceleration (a). An ADXL345 accelerometer and an Arduino Nano were used to measure the jerk in the elevator. Integrating these components ensured precise control, smooth operation, and minimal jerk. In contrast to conventional elevator control circuits that use basic microcontrollers or PLCs with simpler control techniques, this design leveraged the high computational capacity of the TMS320F28335 DSP. This enabled complex control algorithms, such as DTC with S-curve profiles, dramatically minimizing jerk and improving ride comfort. Conventional systems typically use simple relay-based switching or transistor modules, while this design incorporated the PS219B2-CS intelligent power module for efficient switching and integrated protection. The addition of an encoder provided precise feedback on motor position and speed compared to traditional configurations with simple sensors and limit switches. This solution also included current and voltage sensors for real-time monitoring, ensuring optimal performance and reliability.

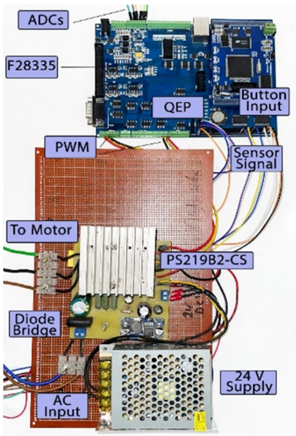

Fig. 5. Elevator control circuit.

VI. RESULTS

The jerk data of the elevator prototype showed considerable variations with and without an S-curve motion profile for both no-load and load circumstances. An empty car is essential for jerk profile analysis, as it sets a benchmark, validates the control system, and suggests improvements. Excessive jerk values were reduced by optimizing the S-curve profiles for smoother operation. This basic analysis was used for load testing, revealing the elevator performance under all load scenarios. Figure 6 displays the PWM1A and PWM1B waveforms output from the DSP at a frequency of about 10 kHz. Figure 7 shows the acceleration data when using a trapezoidal profile speed. On the other hand, Figure 8 illustrates the jerk data, which exhibit significant variability marked by distinct peaks and troughs. The maximum positive jerk value was approximately 3.9 m/s³, whereas the minimum (most negative) jerk values were around -4.7 m/s³. Fluctuations in acceleration can cause discomfort for passengers and put additional stress on the mechanical parts of the elevator.

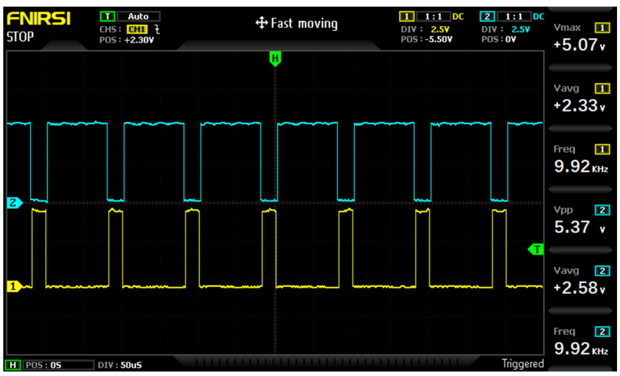

Fig. 6. PWM signals from DSP.

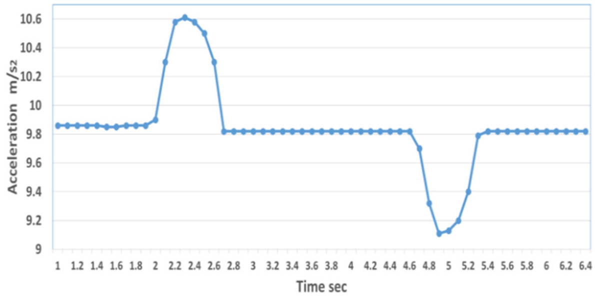

Fig. 7. Acceleration profile without S-curve.

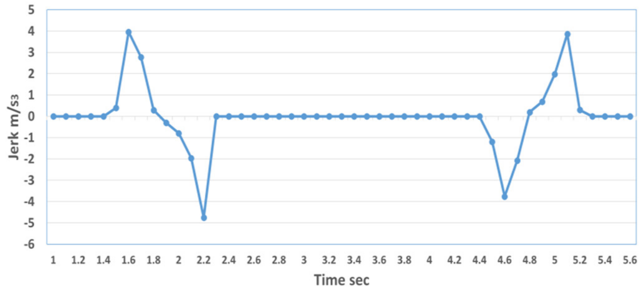

Fig. 8. Jerk profile without S-curve.

In the case of using the S-curve shown in Figures 9 and 10, the S-curve profile effectively enhanced the smoothness of the transitions, resulting in the most notable enhancements. The peak positive jerk was around 1.67 m/s³, whereas the lowest jerk recorded was -1.65 m/s³. The implementation of the S-curve successfully reduced the effects of the additional weight, resulting in improved transitions and increased comfort for passengers.

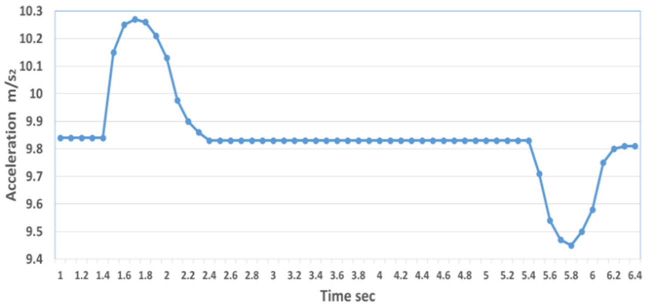

Fig. 9. Acceleration profile with S-curve.

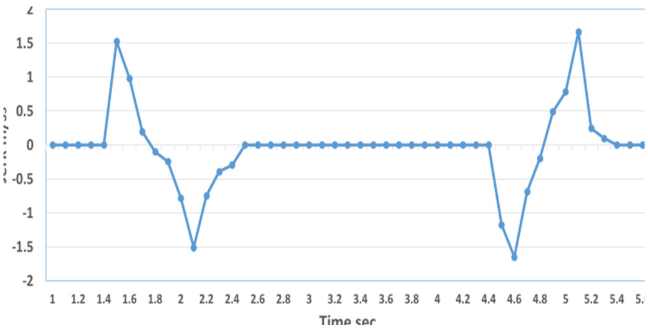

Fig. 10. Jerk profile with S-curve.

Figure 11 illustrates the contrast in jerk profiles of an elevator system between two control scenarios: one without an S-curve and the other with an S-curve.

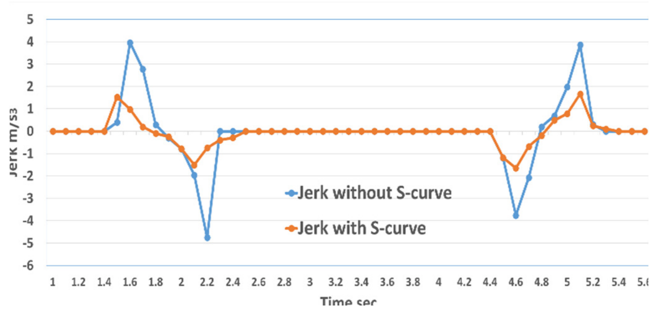

Fig. 11. Jerk profile comparison in both cases.

VII. CONCLUSIONS

The S-curve motion profile, implemented through the DTC technique and controlled by the TMS320F28335 DSP, is designed to significantly reduce jerk and ensure smoother elevator movement. The results indicate that the S-curve profiles reduce elevator jerk by approximately 57.2% compared to when they are not used. This notable improvement underscores the effectiveness of S-curve profiles in minimizing sudden changes in acceleration, thereby enhancing the smoothness and safety of elevator operations. The S-shaped curve is particularly effective in heavy-load situations, providing substantial improvements in reducing sudden acceleration changes. These improvements contribute to a more comfortable ride and reduce mechanical degradation, thus increasing the efficiency of the elevator system. According to ISO 8100-34:2021, elevator jerks should not exceed 1.2 m/s². In these experiments, DTC with S-curve profiles produced a maximum jerk of 1.6 m/s². Although this exceeds the ISO requirement, it performs better than conventional methods that often result in higher jerk values. While the current DTC with S-curve profiles does not meet the ISO standard, it shows significant potential to improve riding comfort by reducing jerk. To meet the ISO 8100-34:2021 limit, further optimization of the S-curve profiles and the DTC algorithm is necessary, along with adjustments to the elevator's mechanical setup and load management. Despite not yet being ISO-compliant, this approach marks a promising step toward improved elevator performance and passenger comfort.

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