

Modeling of Feed Energy Consumption in Fused Deposition Modeling Print Head

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Abstract

This paper proposes a mechanism-based energy consumption modeling method for manufacturing processes. It investigates the energy consumption characteristics of the printhead stepping motion during Fused Deposition Modeling (FDM) and constructs a corresponding energy consumption model through experiments. The power variations and energy consumption levels during the printing process of a typical part were tested and evaluated, with results validating the effectiveness of the constructed model and the proposed method.

Keywords

Fused Deposition Modeling; Mechanism Modeling; The Print Head of 3D Printer.

1. Introduction

Fused Deposition Modeling (FDM) is a common 3D printing technology. Since its emergence in the 1990s, it has gained widespread application in fields such as food [1], aerospace [2], and healthcare [3] due to its advantages including lower equipment costs, ease of operation, and broad material selection [4]. During the FDM process, energy consumption is a significant factor that cannot be overlooked [5]. To produce a model of identical quality, a 3D printer consumes approximately 50 to 100 times more electrical energy than injection molding [6]. This not only directly impacts production costs but also affects production efficiency and environmental sustainability.

Optimizing process parameters for FDM energy consumption is a complex and meticulous process requiring comprehensive consideration of multiple factors. Wang Qiang et al. [7] designed an orthogonal experiment and employed response surface methodology to analyze how key parameters—bed temperature, nozzle temperature, printing speed, and layer thickness—influence energy consumption trends. Yang Shaoyuan et al. [8] utilized Taguchi methodology experiments to determine the effects of processing parameters on energy consumption and processing time. Zhang Lei et al. [9] addressed the carbon emission characteristics of FDM by establishing an energy efficiency optimization model using a BP neural network. Solving this model with an adaptive microhabitat genetic algorithm yielded a response model linking process parameters to energy efficiency. They also investigated the impact of the retraction speed parameter [10]. Osman et al. [11] employed the life cycle assessment (LCA) method to estimate the environmental impact of all identified steps throughout the life cycle using an energy consumption model. Yan et al. [12] subdivided FDM to construct working time and power models for each energy-consuming component or processing stage of FDM 3D printers, enabling more refined energy consumption management and optimization.

In summary, existing energy consumption studies primarily focus on the impact of processing parameters on energy consumption. Few energy consumption models are based on data or algorithms,

and research on energy consumption mechanisms remains relatively weak. Therefore, this paper investigates energy consumption modeling methods based on mechanism analysis, specifically examining the energy consumption characteristics of the printhead stepping motion during the fused deposition modeling process.

2. Theory of FDM Printhead Feed Process

2.1 Structure of FDM-Type 3D Printers

The structure of a 3D printer is relatively complex, with its main components shown in Figure 2. G-Code instruction files are copied to the printer via storage media. Under the precise control of the system, the print head nozzle and build platform are preheated to a specified temperature to ensure the material melts smoothly and adheres to the platform during printing. The heating block within the print head assembly melts the filament material, which is then extruded through the nozzle. The control system directs the print head to move along a predetermined path within the X-Y coordinate system based on G-Code instructions, depositing the extruded molten material layer by layer onto the build platform in the shape of the intended cross-section. After completing each layer, the print bed descends along the Z-axis by a height equal to the layer thickness, driven by a stepper motor, to prepare for the next layer. This process repeats continuously until the entire 3D model is fully constructed.

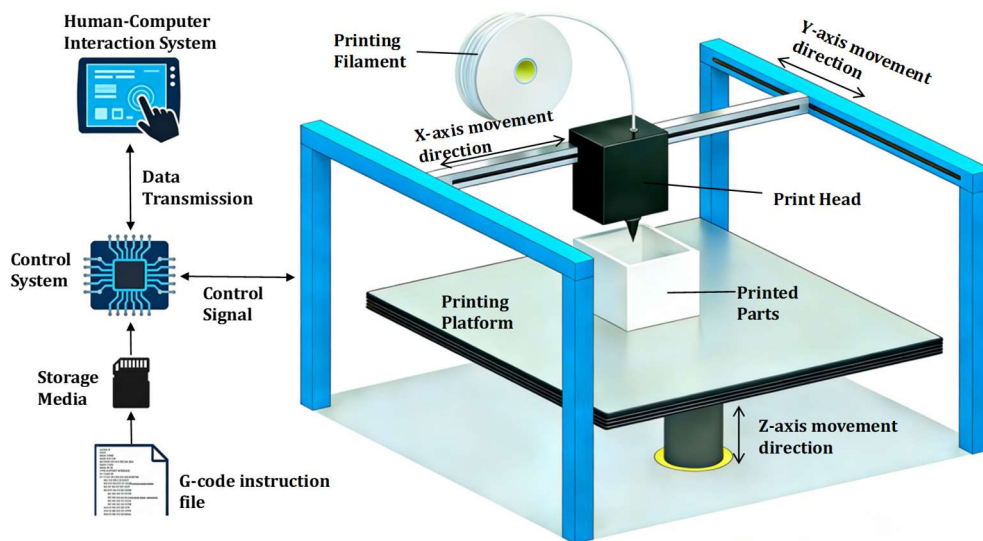


Figure 1. Schematic Diagram of FDM-Type 3D Printer Equipment Structure

2.2 Printhead Process Analysis

The print head of an FDM 3D printer is driven by X-Y axis motion mechanisms, with the X and Y axis motors operating independently without interference. Taking a gantry structure as an example, the print head moves horizontally along the X-axis via a single guide rail. During Y-axis feed, the dual-rail mechanism drives the entire print head assembly (including the X-axis rail) along the Y-axis. Consequently, the Y-axis must handle a heavier load, resulting in slightly higher feed power consumption than the X-axis.

Even when the print head remains stationary on either the X or Y axis, the corresponding feed motors still output torque to maintain position, representing holding power. If the device executes a Y-axis feed command directly from standby without performing a zero-return operation, the power meter reading will only decrease slightly after the Y-axis feed pauses. It will not return to the standby power level, as shown in the second segment of the Y-axis stepping power in Figure 3. The power variation pattern during the third segment of the X-axis feed process in Figure 3 is consistent with that of the Y-axis.

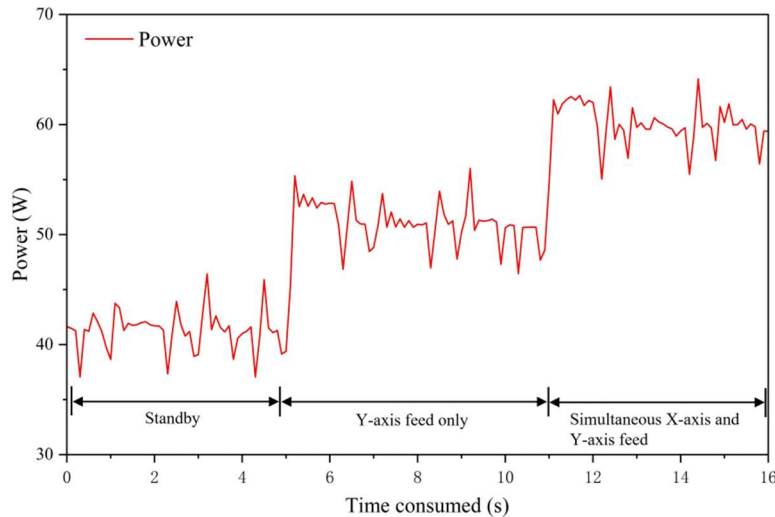


Figure 2. Printhead Power Analysis

3. Mechanism-Based Modeling for Printhead Step Energy Consumption

3.1 Energy Consumption Theoretical Model

(1) Standby Power Consumption $P_{standby}$

Standby mode refers to the state where the printer remains powered on after startup, maintaining basic power supply while awaiting print commands. Once the machine reaches stable operation, standby power consumption $P_{standby}$ remains largely unchanged, stabilizing around a fixed value.

$$P_{standby} = \frac{\sum_{i=1}^N P_{standby-i}}{N} \quad (1)$$

In the formula, $P_{standby-i}$ denotes the i -th power value collected (in watts); N represents the number of collection points.

(2) Printhead Stepping Power

The three sets of motors driving the printhead's horizontal X/Y-axis movement within the print space coordinate system and the vertical Z-axis movement of the print platform operate independently.

After completing the reset operation, the stepper motors enter standby mode. By sequentially energizing the stator windings, the stepper motors generate a rotating magnetic field that drives the rotor to move at a fixed step angle. If the driver continuously energizes the windings, the rotor remains at its current position due to magnetic force, creating a “self-locking” effect that resists minor external disturbances to maintain printhead stability. The power consumption at this state is denoted as P_0 .

When receiving a print head movement command, the power consumption required for the stepper motor to drive the print head movement is

$$P_F = T_{ts}\omega_m + P_0 = T_{sr}\omega_m + B\omega_m^2 + P_0 \quad (2)$$

In the formula, T_{ts} represents the total static torque equivalent to the motor shaft from the feed system (unit: N·m), B denotes the equivalent hysteresis damping coefficient; ω_m is the angular velocity of the feed motor (unit: rad/s). To express this angular velocity in terms of machining speed, it is calculated as:

$$\omega_m = \frac{2\pi}{60} n_m = \frac{2\pi r_g}{60} n_l = \frac{2\pi r_g v}{60 h_p} \quad (3)$$

In the formula: n_m is the motor rotational speed (unit: r/min), n_l is the lead screw rotational speed (unit: r/min), r_g is the gear reduction ratio; v is the horizontal feed speed (unit: mm/min), h_p is the lead screw pitch (unit: mm).

The motor shaft and guide rail shaft are connected via reduction gears. Therefore, the relationship between the equivalent torque T_{sr} on the motor shaft and the total static torque T_s equivalent to the guide rail shaft is expressed as follows:

$$T_{sr} = \frac{T_s}{r_g} \quad (4)$$

According to Reference [13], the loads acting on the guide rail primarily originate from the guide rail friction torque T_f , bearing friction torque T_z , and load reaction torque T_r . These three loads are expressed as follows:

$$\begin{cases} T_f = \frac{h_p}{2000\pi} \mu_f (m_z g + f_{squ}) \\ T_z = \frac{d_z}{2000} \mu_z (F_{f1} + F_p) \\ T_r = \frac{h_p}{2000\pi} F_{f1} \end{cases} \quad (5)$$

Summing the three expressions in (5) yields the total static torque T_s on the guide rail shaft.

$$T_s = T_f + T_z + T_r \quad (6)$$

In the formula, μ_f represents the coefficient of friction between the moving component and the guide rail; m_z denotes the total mass of the feed motion component (unit: kg); g is the gravitational acceleration (approximately 9.8 m/s²); f_{squ} represents the force exerted by the nozzle extrusion and printing platform friction acting on the print head section (unit: N). In the formula, d_z is the average diameter of the bearing (unit: mm); μ_z is the friction coefficient of the bearing; F_{f1} is the reaction force of the extrusion feed motion (unit: N); F_p is the preload force acting on the bearing (unit: N). Substituting equations (3) to (6) into equation (2) yields:

$$P_F = \frac{h_p \mu_{gf} m_z g + \pi \mu_z d_b F_p}{60000 h_p} v + \frac{4\pi^2 r_g^2 B}{3600 h_p^2} v^2 + P_0 \quad (7)$$

In a specific 3D printer system, assume:

$$C = \frac{h_p \mu_{gf} m_z g + \pi \mu_z d_b F_p}{60000 h_p}, \quad D = \frac{4\pi^2 r_g^2 B}{3600 h_p^2} \quad (8)$$

C and D are both constants, then we have:

$$P_F = Cv + Dv^2 + P_0 \tag{9}$$

The X-axis and Y-axis stepper motors operate on the same principle but handle different feed loads, therefore:

$$\begin{cases} P_{FX} = C_x v + D_x v^2 + P_{0x} \\ P_{FY} = C_y v + D_y v^2 + P_{0y} \end{cases} \tag{10}$$

It is worth noting that during continuous printing of parts, the motors of each axis may remain in a holding state for extended periods. Consequently, P_{0x} and P_{0y} in Equation (10) persist throughout the entire printing cycle of the part, contributing alongside standby power to the printer's background power consumption.

3.2 Experimental Methods

The experimental 3D printer model is the Juying T10000, procured from Shenzhen Juying Investment Development Co., Ltd. Printing materials consist of 1.75mm diameter white PLA filament and blue ABS filament. A WT333E power analyzer paired with a laptop running WTVIEWERFree power analysis software was used for power acquisition and analysis, with a data sampling interval of 0.1 seconds.

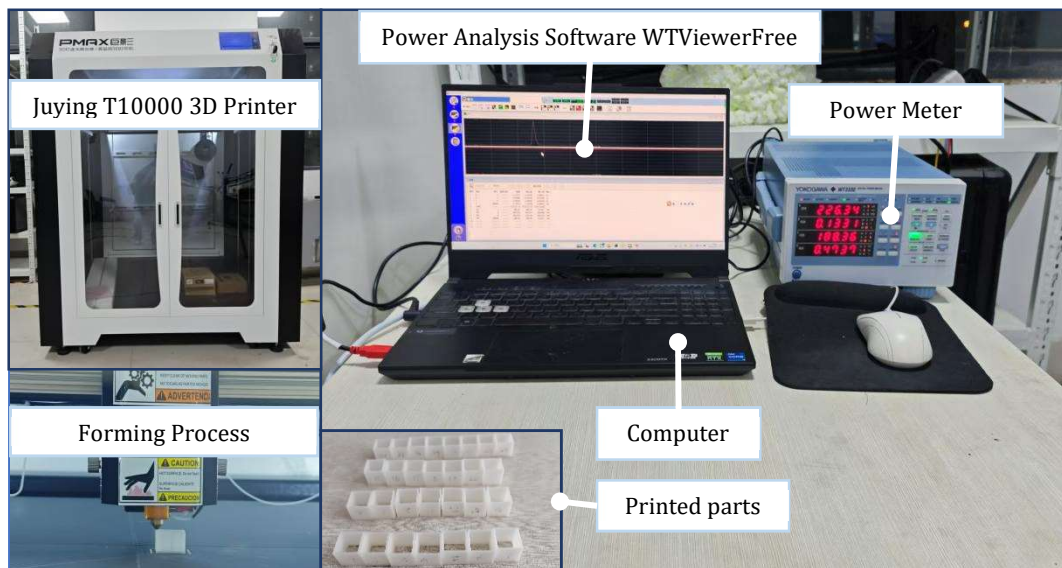


Figure 3. Experimental Platform Setup

(1) Standby Component Power Pstandby

When the 3D printer is powered on but not performing any operations, only the basic modules remain active. The power measured via the experimental platform during this state constitutes the standby power. After the device stabilizes, a 2-minute measurement cycle is established. The printer's power data within each cycle is recorded, and the average standby power for that cycle is calculated accordingly. Repeating the measurement steps yielded the experimental results shown in Table 1. Substituting these values into Equation (1) yields a standby power $P_{standby}$ of approximately 40.71 W.

Table 1. Standby Power Measurement Results

Number of experiments	Mean Power(W)
1	40.84156
2	40.58244
3	40.71069
Average standby power consumption	40.71156

(3) Printhead Stepping Power

To establish the functional relationship between printhead feed power and feed speed, the stepping motor power was measured at different feed speeds. The measurement method was as follows: When the machine performed only X/Y-axis feed motion, the total machine power was measured using a power meter. Subtracting the basic module power yielded the stepping motor power. This experiment measured 11 sets of data at equal intervals within the machine's feed speed range of 0 mm/s to 100 mm/s. The experimental data are shown in Table 2. Further analysis employed Origin 2025 graphical visualization and data analysis software to perform quadratic polynomial fitting on the experimental data. The fitting results are shown in Figure 4. Based on the results, we obtained:

$$\begin{aligned}
 C_x &= 0.13528 & C_y &= 0.1178 \\
 D_x &= -9.74621 \times 10^{-4} & D_y &= -6.99059 \times 10^{-4} \\
 P_{0x} &= 8.23239 & P_{0y} &= 7.90962
 \end{aligned}$$

Therefore, the printhead stepping power model is expressed as:

$$\begin{cases}
 P_{FX} = 0.13528v^2 - 9.74621 \times 10^{-4}v + 8.23239 \\
 P_{FY} = 0.1178v^2 - 6.99059 \times 10^{-4}v + 7.90962
 \end{cases} \quad (11)$$

Table 2. X/Y-Axis Step Power Data Acquisition

X-axis stepping speed(mm/s)	X-axis stepping power(W)	Y-axis stepping speed(mm/s)	Y-axis stepping powe(W)
0	8.23239	0	7.90962
10	9.54088	10	8.70497
20	10.32727	20	9.73758
30	11.1859	30	10.63843
40	12.00972	40	11.29308
50	12.76381	50	12.23773
60	13.10411	60	12.66288
70	12.99286	70	12.81412
80	12.54631	80	12.89226
90	12.63838	90	12.80284
100	11.94797	100	12.52105

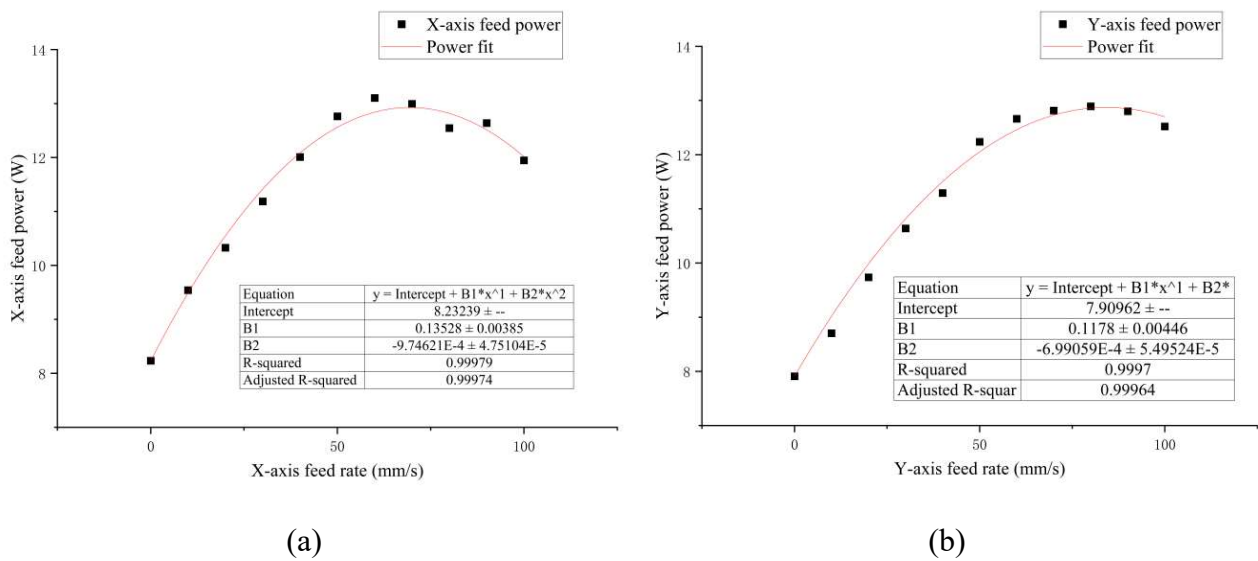


Figure 4. X/Y-Axis Step Power Fitting Results (a. X-Axis Fitting b. Y-Axis Fitting)

4. Conclusion

In summary, this study successfully addressed the core challenge of modeling the energy consumption of the printhead stepping process during FDM fabrication through a combination of mechanism analysis and experimental research. The proposed modeling approach is scientifically sound and feasible, and the constructed energy consumption model demonstrates high accuracy and practicality. This work not only enriches the research perspectives and methodologies for modeling FDM processing energy consumption but also provides a theoretical basis and technical support for optimizing printing parameters, reducing processing energy consumption, and enhancing production efficiency in actual manufacturing.

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