A Traveling-Wave Linear Ultrasonic Motor Driven by Two Torsional Vibrations: Design, Fabrication, and Performance Evaluation

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ABSTRACT In this study, we design and fabricate a tank-track-shaped stator working in two torsional modes to form a traveling-wave (TW) linear ultrasonic motor (USM). The stator comprises two torsional transducers and two kidney-shaped vibrating bodies. When voltages with a certain phase are applied to the transducers, two in-phase TWs are excited on the vibrating bodies to frictionally drive the slider. Here, the torsional vibration guarantees strong electromechanical coupling, and meanwhile, the tank-track shape ensures plural driving points and low weight; these features may facilitate realizing high thrust force density and high power density of linear motors. To examine the feasibility, first, we constructed a stator prototype 116 mm in length, 91 mm in width, and 32 mm in thickness and explored its vibration properties. The minimal standing wave (SW) ratio reaches 1.21 and the small SW components are desirable for TW motors. Then, we measured the load characteristics and found that, at the working frequency of 54.34 kHz and the phase shift of $-110^\circ$, the maximal thrust force and maximal output power were 96.1 N and 27.8 W, respectively. Moreover, the thrust force density and power density reached respectively 234.1 N/kg and 67.8 W/kg, relatively high compared to the values of most conventional linear motors. This study verifies the feasibility of our proposal and paves a new way of designing powerful linear USMs.

INDEX TERMS Linear ultrasonic motor, torsional vibration, traveling wave, thrust force density, power density.

I. INTRODUCTION

Ultrasonic motors (USMs) convert electrical energy to mechanical energy on the basis of inverse piezoelectric effect and achieve actuation by frictional force [1]–[3]. Different from electromagnetic motors, they possess the merits of quick response, self-locking at the power-off state, and absence of electromagnetic radiation [4]–[6]. In particular, linear USMs are potentially applicable to some electromechanical system (e.g., precision instruments and optical devices) [6]–[9] as some of them have satisfactorily large outputs (e.g., the maximal thrust force is $\sim$50 N and the maximal output power is $>20$ W) [10]–[13]. However, their thrust force densities and/or power densities are generally not high enough; this probably deteriorates the controllability of electromechanical system [14], [15]. Thus, it is necessary to enhance thrust force densities and power densities of linear USMs.

It is known that vibration modes have fundamental effect on thrust force density and power density [16], [17]. To date, linear motors mainly operate in bending/bending ($B^2$), longitudinal/longitudinal ($L^2$), and bending/longitudinal ($B/L$) modes [6]–[13], [18]–[21]. First, $B^2$ modes have been heavily exploited in conventional USMs. For instance, Liu et al. [2] excited two orthogonal bending vibrations on the stator’s bilateral ends to form a standing-wave (SW) motor. Kondo et al. [22] bonded two groups of lead-zirconate-titanate (PZT) elements onto two ends of a rectangular bar and generated a traveling wave (TW) on the middle part to drive the slider. In general, lightweight is achievable with $B^2$ motors [1], [10], [23], [24], but their mechanical outputs are limited as electromechanical system
coupling of bending vibration is not strong [25], [26]. Second, several motors utilize L2 modes as longitudinal vibration generally exhibits high electromechanical coupling [1], [3]. For example, Ting et al. [8] arranged two Langevin-type transducers in orthogonal directions and used the elliptical motions on connecting points of two transducers to achieve actuation; this method, however, limits the number of driving feet, resulting in low mechanical outputs [12]. Third, some motors are achieved by combining B/L vibrations [5], [9], [22]. Taking Yun et al.’s motor [9] as a typical example, its thrust force density reaches 202 N/kg, relatively high among linear motors with satisfactory performance. However, since its transducer should be sufficiently long to generate large driving force, the thrust force density and/or power density are seemingly difficult to increase through minimization.

In this study, we employ two torsional vibrations to form a TW linear motor. Here, two kidney-shaped vibrating bodies are connected onto bilateral surfaces of two parallelly-arranged torsional transducers to form a tank-track-shaped stator. Since the torsional transducers work in the 2nd modes, the bilateral surfaces oscillate in phase [26]. As a consequence, two TWs are excited on the vibrating bodies to drive the slider. Here, torsional/torsional (T2) modes are chosen for the following reasons: First, electromechanical coupling is stronger for torsional vibration than for bending vibration [27], [28]; this may enhance the-stator-induced driving force [1], [10]. Second, since two TWs in phase exist on the vibrating bodies, whose lengths are smaller than one wavelength, it can be equivalently regarded that this motor has two driving feet [1], [14], [22]; this also contributes to enhancing driving force. Third, the stator’s tank-track-shaped framework seemingly facilitates realizing lightweight. On the other hand, linear motors with T2 modes have been rarely been reported up to now. Thus, it would be meaningful to test whether using T2 modes can increase thrust force densities and power densities of linear motors.

In this paper, first, we designed and fabricated a T2 stator to form a TW linear motor and systematically explored its vibration properties. Then, we investigated the load characteristics and made comparison with several conventional linear USMs.

II. DESIGN OF T2 MOTOR
A. OVERALL STRUCTURE
As Fig. 1 depicts, the tank-track-shaped stator consists of two cylindrical transducers and two kidney-shaped vibrating bodies. To achieve lightweight, the transducers and vibrating bodies are made of duralumin (A7075) for its low density [29]. Besides, four groups of torsional PZT disks are arranged at the transducers’ nodes to efficiently generate the 2nd torsional vibration, causing the bilateral surfaces to oscillate in phase. The used PZT is P51, produced by Yuke Corporation (Baoding, China) and its elastic, piezoelectric, and dielectric matric are as follows:

\[
[e^E] = \begin{bmatrix}
78 & 42 & 20 & 0 & 0 & 0 \\
42 & 78 & 20 & 0 & 0 & 0 \\
20 & 20 & 72 & 0 & 0 & 0 \\
0 & 0 & 0 & 26 & 0 & 0 \\
0 & 0 & 0 & 0 & 23 & 0 \\
0 & 0 & 0 & 0 & 0 & 23 \\
\end{bmatrix} \text{(GPa),}
\]

\[
[d] = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0.70 & 0 \\
0 & 0 & 0 & 0 & 0.70 & 0 & 0 \\
-0.19 & -0.19 & 0.45 & 0 & 0 & 0 & 0 \\
\end{bmatrix} \times 10^{-9} (\text{C/N}),
\]

and

\[
[e^S] = \begin{bmatrix}
22.13 & 0 & 0 \\
0 & 22.13 & 0 \\
0 & 0 & 15.93 \\
\end{bmatrix} \times 10^{-9} (\text{F/m}),
\]

respectively. Note that, in the elastic matrix, c11, c33, and c55 are provided by the maker, and the other parameters are derived as c44 = c33/2(1 + σ), c12 = c11 − 2c55, and c13 (c23) = c33 − 2c44, where σ stands for the Poisson’s ratio [30]. The PZT disks and middle portions are tightly clamped with threaded parts of the stainless-steel shafts. Each vibrating body includes two semi-circular portions and a rectangular portion. Here, the semi-circular portions’ diameters equal those of the transducers. The procedures of deciding the dimensions are introduced later. In addition, holes are created to insert the transducers into vibrating bodies. The procedures of assembling the stator is given in Appendix. A slider with a rectangular framework is pressed onto the stator and two poly-phenylene-sulfide sheets are glued onto the slider’s bottom surface as frictional materials.

Fig. 2 illustrates the PZT disks’ polarization directions and the method of applying voltage. The PZT disks are polarized along circumferential directions and each group contains two disks with opposite polarization directions. Phosphor-bronze electrodes are clamped onto the PZT disks’ lateral surfaces for applying voltage. When two voltages with a certain phase shift are applied, as shown in Fig. 3, two torsional vibrations...
are excited on the transducers and transferred into TWs on the vibrating bodies. As a result, elliptical motions exist on the upper surfaces and frictionally drive the slider.

**B. DESIGN PROCEDURE**

To obtain high thrust force density and high power density, we investigate how the $k_{\text{eff}}/m$ ratio changes with varying dimension (where $k_{\text{eff}}$ and $m$ are respectively the effective electromechanical coupling factor and the stator’s weight). Here, we focus on $k_{\text{eff}}$ as it markedly affects USMs’ mechanical outputs [2], [31], [32]. Besides, the resonance frequency $f$ should be in the inaudible range (>20 kHz) to avoid the existence of noise.

1. Set the PZT disk’s diameter $d_p$ and thickness to respectively 30 and 4 mm (see Fig. 1) as torsional PZT in this size is easy to produce [28].

2. Make the torsional transducer’s diameter $d_T$ equal to $d_p$. For the 2nd torsional vibration,

$$f = \frac{1}{l_T} \cdot \sqrt{\frac{E}{2(1+\sigma)\rho}},$$  

where $l_T$ denotes the transducer’s length, and $E$, $\sigma$, and $\rho$ represent the shear modulus (70.7 GPa), Poisson’s ratio (0.33), and density ($2.8 \times 10^3$ kg/m$^3$) of A7075, respectively.

3. Determine the rectangular portion’s length $l_r$. To excite TWs,

$$l_r = \frac{1 + 2n}{4} \cdot \lambda_B,$$

where $n$ stands for an integer and $\lambda_B$ denotes the wavelength corresponding to the bending vibration [1]. When $l_r = \lambda_B/4$, the distance between two torsional transducers’ axes is likely smaller than $d_T$; this easily causes insufficient space for the transducers. On the other hand, considering the requirement of low weight, we set that [27], [33]

$$l_r = \frac{3}{4} \lambda_B = 1.01 \cdot \left(\frac{h_r}{d_T}\right)^\frac{1}{2} \cdot \left(\frac{E}{\rho}\right)^\frac{1}{4},$$

where $h_r$ ($= d_T$) stands for the rectangular portion’s height. Besides, the vibrating bodies have thicknesses of 10 mm, sufficiently high to obtain steady connection.

4. Calculate $k_{\text{eff}}$ through finite element analysis, of which the detailed procedures are given in [4] and [31]. In the meantime, $m$ is derived by accumulating each part’s weight.

Figs. 4(a) and (b) respectively show how $k_{\text{eff}}/m$ ratios and $f$’s depend on $l_T$s. Clearly, the $k_{\text{eff}}/m$ ratio reaches the peak value at $l_T = 40$ mm. Meanwhile, $f$ equals ~50 kHz, locating in the inaudible range. According to Eq. 3, $l_r = 60.7$ mm.

5. Create 1-mm-deep 1.5-mm-wide teeth (see Fig. 1) on upper and bottom surfaces of vibrating bodies to enlarge vibration amplitude. Here, the number of teeth is 19 for each surface.

Fig. 5 shows the stator prototype (weight: 0.41 kg). The stator is supported with shafts. Since the torsional vibration velocities are theoretically zero in torsional transducers’ axes [16], this support method should exhibit negligibly small effect on the vibration properties [14].
FIGURE 4. (a) Electromechanical coupling factors, entire stator’s weight, and their ratio as well as (b) the resonance frequency versus torsional transducer’s length.

III. VIBRATION PROPERTIES

First, the equivalent circuit parameters of the stator were explored with an impedance analyzer (4294A, Agilent, Santa Clara, USA). The resonance frequency $f_r$, anti-resonance frequency $f_a$, motional admittance $Y_{m0}$, and bandwidth corresponding to 0.707 times of peak admittance $\Delta f$ were obtained from the admittance curves (note that they were measured when the transducers connected the vibrating bodies). Using these values, $k_{\text{eff}}$, mechanical quality factor $Q_m$, motional resistance $R_m$, motional capacitance $C_m$, and motional inductance $L_m$ were estimated as [4], [14], [34]

\begin{align*}
    k_{\text{eff}} &= \sqrt{\frac{f_a^2 - f_r^2}{f_a^2}}, \\
    Q_m &= \frac{f_r}{\Delta f}, \\
    R_m &= \frac{1}{Y_{m0}}, \\
    C_m &= \frac{Y_{m0}}{2\pi f_r Q_m}, \\
    L_m &= \frac{Q_m}{2\pi f_r Y_{m0}},
\end{align*}

respectively. Table 1 lists the equivalent circuit parameters. Observably, $f_r$ s have a discrepancy of <0.4 kHz between two torsional transducers; this facilitates the excitation of TWs. Besides, the calculated value of $k_{\text{eff}}$ is $\sim 30\%$ (see Section II), in good agreement with the experimental results.

Subsequently, the vibration velocity distribution was investigated via interferometric measurement [35]. The voltages were applied with power amplifiers (HSA4051, NF Corporation, Yokohama, Japan). As shown in Fig. 6, the stator was supported onto a frame and the $\zeta$-axis vibration velocities on the upper surfaces of the vibrating bodies were measured with a laser Doppler vibrometer (LV-S01, Sunny Optical Technology Corp., Yuyao, China). The phase
TABLE 1. Equivalent circuit parameters.

| Parameters                        | Transducer No. 1 | Transducer No. 2 |
|-----------------------------------|-------------------|-------------------|
| Resonance frequency $f_r$ [kHz]   | 54.482            | 54.868            |
| Anti-resonance frequency $f_a$ [kHz] | 57.098           | 57.878            |
| Electromechanical coupling factor $K_{e}$ | 30.4%            | 31.8%             |
| Mechanical quality factor $Q_m$   | 195               | 182               |
| Motional admittance $Y_m$ [mS]    | 10.2              | 11.0              |
| Motional resistance $R_m$ [Ω]     | 97.8              | 90.7              |
| Motional capacitance $C_m$ [nF]   | 0.153             | 0.176             |
| Motional inductance $L_m$ [mH]    | 55.8              | 47.8              |

difference between the vibration velocity and a reference signal was obtained with an oscilloscope (MSO2000B, Tektronix, Oregon, USA). The driving voltage, working frequency, and phase shift were respectively set to 20 V, 54.34 kHz, and $-110^\circ$. In this paper, the voltage and the vibration velocity are given as zero-to-peak values.

Figs. 7(a) and (b) respectively show how the $z$-axis vibration velocities are distributed on left and right vibrating bodies.
bodies. The phase difference gradually decreases from 120° to -150°, implying the successful excitation of TWs [34]. On the left vibrating body, the average vibration velocity is 143 mm/s, close to the value of the right vibrating body (144 mm/s); this can suppress frictional loss [1], [14], [36], [37]. Besides, the SW ratios (defined as \( v_{\text{max}} / v_{\text{min}} \) ratios, where \( v_{\text{max}} \) and \( v_{\text{min}} \) respectively denote maximal and minimal vibration velocities [38]) on the left and right vibrating bodies are 1.21 and 1.24, respectively, inferring that the SW components are satisfactorily small.

Finally, the relationship between the SW ratios and the phase shifts were explored. On condition that two SWs have a phase difference of 3\( \pi /2 \) (corresponding to 3\( \lambda_B /4 \)) in space and a phase shift \( \psi \) in the time domain, through superposition, the waves propagating on the vibrating bodies are expressed as [39]

\[
A_0 \cos (2\pi ft) \cos \left( \frac{2\pi}{\lambda_B} \cdot x \right) + A_0 \cos (2\pi ft + \psi) \cos \left( \frac{2\pi}{\lambda_B} \cdot x + \frac{3\pi}{2} \right) = A_0 \cos \left( 2\pi ft + \frac{2\pi}{\lambda_B} \cdot x \right) + A_0 \sin \left( \frac{2\pi}{\lambda_B} \cdot x \right) \sin (2\pi ft + \psi),
\]

where \( A_0 \) stands for vibration amplitude. At \( \omega t = 0 \), magnitudes of the TW and SW components should be \( |A_0| \)
and \(|A_0\cos(\phi)|\), respectively. Thus,

\[
SW \, ratio = \frac{1 + |\cos (\phi)|}{1 - |\cos (\phi)|}.
\]  (10)

Figs. 8(a) and (b) respectively plot the variations of SW ratios on the left and right vibrating bodies against the phase shift. Observably, the theoretical and experimental results show approximately the same tendencies. Since the two torsional transducers’ admittance characteristics are not completely identical, their vibration amplitudes show small difference, which is a probable reason for the discrepancy between theoretical and experimental results [39]. In addition, the TW ratios provide minimum values when the phase shifts are \(-110^\circ\) and \(80^\circ\).

**IV. MOTOR PERFORMANCE**

**A. LOAD CHARACTERISTICS**

Fig. 9(a) illustrates the testbed for evaluating the T² motor’s load characteristics. The thrust force was estimated by pulling up weights and the sliding speed was measured with a velocimeter (HG200, Aero-top Hi-tech Corp., Beijing, China). The input power was recorded using high-frequency power meters (3333, Hioki E. E. Corp., Nagano, Japan).

Fig. 9(b) shows the entire motor’s configuration. As mentioned above, the stator was supported with the frame that connected the pillars. One side of a linear guide was fixed to the slider while the other side was pressed with a board, capable of freely sliding along the pillars. Moreover, two coil springs were compressed to apply the preload to the motor. Here, the preload was estimated from the spring-stiffness coefficient and the spring’s deformation. During the experiments, the working frequency and the phase shift were respectively set to \(\sim 54.34 \, \text{kHz}\) and \(-110^\circ\).

Figs. 10(a), (b), and (c) show how the sliding speed, output power, and efficiency depend on the thrust force, respectively, at 250 V. When a 240 N preload was applied, the no-load sliding speed was 1470 mm/s and the maximal thrust force was 41.2 N. When the preload increased to 480 N, the maximal thrust force reached 96.1 N. At a 360 N preload, the maximal output power and the maximal efficiency were respectively 27.8 W and 27.9%.

Figs. 11(a), (b), (c), and (d) respectively show maximal thrust force, no-load sliding speed, maximal output power, and maximal efficiency as functions of the driving voltage.
voltage. When the voltage ranged from 25 to 250 V, the no-load sliding speed exhibited a gradual enhancement. The output power and efficiency corresponding to 360 N were higher than those to 240 and 480 N probably because the frictional loss was smaller [40], [41]. Most TW motors cannot provide high efficiencies as the vibration velocities differ among the driving feet [21], [31], [35]. In contrast, only one wave crest exists on each vibrating body; this may suppress vibration-velocity-difference-induced frictional loss and consequently enhance the efficiency.

### B. PERFORMANCE COMPARISON

Figs. 12(a) and (b) respectively plot the maximal thrust forces and maximal output powers of some linear motors against their stators’ weights. The $T^2$ motor exhibits the thrust force density and power density of respectively 234.1 N/kg and 67.8 W/kg, relatively high compared to the values of most conventional ones. By comparing vibration properties and load characteristics of some typical motors, we get several possible reasons for high thrust force density and high power density of the $T^2$ motor.

1. For the $B^2$-2 motor, the PZT elements respectively work in the transverse ($d_{31}$) and shear ($d_{15}$) modes [7]. Consequently, the $B^2$-2 motor’s $k_{eff}$ (8.4%) is 0.27 times that of the $T^2$ one (30.4%); this limits the thrust force density and power density of the $B^2$-2 motor [17].

2. Though the $L^2$-1 motor’s $k_{eff}$ (26.6%) is comparable to that of the $T^2$ one, it has one driving foot [9], which probably results in the relatively low thrust force [12].

3. Despite the small profile, the B/L-1 motor (in cylindrical shape) has larger weight, resulting in lower thrust force density and lower power density than the $T^2$ motor (in tank-track shape) [11]. It is also worth mentioning that, owing to identical configurations, two torsional transducers of the $T^2$ motor have approximately the same $f_s$, ensuring
its structural adaption to various application areas [1], [21]; this would be another advantage of the T^2 motor over the B/L one.

To sum up, high thrust force density and high power density are achievable with linear motors by using T^2 modes; this verifies the feasibility of our proposal. Besides, the production cost of the T^2 motor prototype is ∼300 dollars, twice the cost of the B^2, L^2, or B/L one as a consequence of relatively high expense of torsional PZT; this problem may be tackled in mass production owing to the reduction in PZT’s expense.

V. CONCLUSION

In this study, we designed and fabricated a stator working in T^2 modes and employed it to form a linear motor. The stator incorporated two torsional transducers and two kidney-shaped vibrating bodies. When two voltages with a certain phase shift were applied, two torsional vibrations, excited on the transducers, generated two TWs on the vibrating bodies to frictionally drive the slider. To increase torque density and/or power density, electromechanical coupling factors and weights are discussed by FEA. The load characteristics of the T^2 motor are experimentally evaluated. The maximal thrust force, no-load sliding speed, maximal output power, and maximal efficiency are 96.1 N, 1470 mm/s, 27.8 W, and 27.9%, respectively. Moreover, since the torsional vibration, plural driving feet, and tank-track shape can enhance mechanical outputs and reduce weights, the thrust force density and power density reach respectively 234.1 N/kg and 67.8 W/kg, relatively high among conventional linear USMs.

Through the above investigation, we have gained an understanding on the T^2 motor and anticipate that the results will provide adequate information for structural optimization. In the future, the characteristics of the T^2 motor’s stepping operation will be explored to achieve wider application fields.

APPENDIX

ASSEMBLY OF THE STATOR

The method of forming the tank-track-shaped stator is as follows:

(1) Machine the components, which, as Fig. 13(a) shows, include the kidney-shaped vibrating bodies, shafts, and middle portions. Here, the right vibrating body is structurally different from the left one.

(2) Clamp the middle portions, PZT disks, and parts of the left vibrating body onto the right vibrating body to form torsional transducers [see Fig. 13(b)].

(3) Insert the transducers into the left vibrating bodies’ holes by hammering the vibrating body [see Fig. 13(c)]. Here, the outer surfaces of the connecting parts of the transducers
and the holes adopt interference fit for not only achieving steady connection but also avoiding excessive vibration loss [42], [43].

REFERENCES

[1] S. Ueha, Y. Tomikawa, M. Kurosawa, and K. Nakamura, Ultrasonic Motors: Theory and Applications. New York, USA: Oxford Univ. Press, 1993, pp. 4–13.
[2] Y. Liu, W. Chen, J. Liu, and X. Yang, “A high-power linear ultrasonic motor using bending vibration transducer,” IEEE Trans. Ind. Electron., vol. 60, no. 11, pp. 5160–5166, Nov. 2013.
[3] Q. Zhang, W. Chen, Y. Liu, J. Liu, and Q. Jiang, “A frog-shaped linear piezoelectric actuator using first-order longitudinal vibration mode,” IEEE Trans. Ind. Electron., vol. 64, no. 3, pp. 2188–2195, May 2017.
[4] J. Wu, Y. Mizuno, and K. Nakamura, “Polymer-based ultrasonic motors utilizing high-order vibration modes,” IEEE/ASME Trans. Mechatronics, vol. 23, no. 2, pp. 788–799, Apr. 2018.
[5] L. Wang, V. Hofmann, F. Bai, J. Jin, and J. Twiefel, “Modeling of coupled longitudinal and bending vibrations in a sandwich type piezoelectric transducer utilizing the transfer matrix method,” Mechatronics, vol. 20, pp. 216–237, Aug. 2010.
[6] L. Wang, Y. Guan, Y. Liu, J. Deng, and J. Liu, “A compact cantilever-type ultrasonic motor with nanometer resolution: Design and performance evaluation,” IEEE Trans. Ind. Electron., early access, Jan. 15, 2020, doi: 10.1109/TIE.2020.2965481.

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