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An Embedded Coupled-Motor Platform for Reproducible Experiments on Linear Time-Periodic Systems ⋆

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Abstract: Linear Time-Periodic (LTP) dynamics arise in many electromechanical and robotic systems but remain difficult to study experimentally due to limited reproducible hardware platforms. This paper presents an embedded coupled-motor test bench designed for deterministic realization and analysis of LTP behavior. Two rigidly coupled brushless actuators are controlled at 500 Hz, enabling torque-controlled actuation and multi-signal measurement. Periodic feedback modulation on the load side induces controlled LTP dynamics, producing characteristic harmonic coupling verified through frequency-domain analysis. The platform provides a repeatable experimental environment for validation of LTP modeling, identification, and control methods.

Keywords: Linear Time-Periodic systems, Time/parameter varying system identification, Linear system identification, Experimental system identification, Mechatronic system estimation, identification, control, Embedded control systems, Sampled-data/digital control, Model validation, Mechatronic system modeling

1. INTRODUCTION

The modeling and regulation of periodically varying dynamics have attracted significant interest in applications where Linear Time-Periodic (LTP) behavior arises intrinsically, including wind turbines (Allen et al., 2011), helicopter rotor systems (Hwang, 1997), and legged locomotion (Uyanık İ, 2016). Unlike Linear Time-Invariant (LTI) systems, LTP systems map a single sinusoidal excitation into multiple spectral components shifted by integer multiples of a pumping frequency. This frequency coupling, originating from periodically varying system coefficients or linearization about limit cycles, cannot be captured within classical LTI representations (Mollerstedt and Bernhardsson, 2000; Uyanık İ, 2016). As a result, analysis, identification, and control of such systems require modeling and experimental frameworks that explicitly preserve periodic structure.

Experimental realization of LTP dynamics has received comparatively less attention than theoretical developments. A notable example is the mechanically coupled two-motor test bench introduced by Sert et al. (2023), where periodic velocity-feedback modulation generates an LTP plant. While this platform demonstrated the feasibility of hardware-based LTP experimentation, it was constrained by a 100 Hz loop rate and first order dynamics model. The proposed platform advances this setup by operating deterministically at 500 Hz, ensuring 2 millisecond timing consistency suitable for capturing harmonic interactions. Beyond the increased sampling rate, the shift from velocity-commanded actuation to torque-controlled actuation with synchronized multi-variable sensing (torque, velocity, and position) provides a more informative measurement framework. This capability is particularly relevant for LTP systems, as it facilitates the observation of cross-variable frequency coupling and periodic energy transfer, which are difficult to observe in single-output, lower-frequency configurations.

In parallel with these experimental developments, several identification approaches for LTP systems have been developed, including harmonic transfer representations and frequency-domain subspace methods (Uyanık İ, 2016; Uyanık et al., 2019; Yin et al., 2021). While these methods provide powerful theoretical tools for recovering periodic dynamics, their practical validation and comparative evaluation remain constrained by the scarcity of reproducible datasets. In particular, the lack of synchronized multi-signal measurements generated under deterministic timing limits systematic investigation of periodic energy transfer mechanisms and complicates the benchmarking of identification algorithms.

To address these limitations, this work presents a high-accuracy embedded LTP test bench designed for reproducible dataset generation and algorithm evaluation. By providing synchronized sensing and repeatable execution across experiments, the platform enables frequency-domain characterization of harmonic structures induced by periodic dynamics and provides a consistent experimental basis for benchmarking modern LTP identification and control methods.

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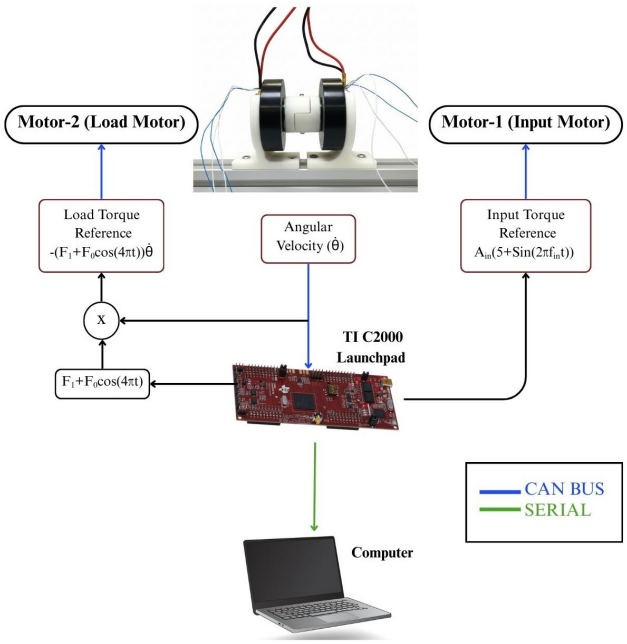


Fig. 1. Embedded coupled-motor LTP test bench. Motor 1 excites the system, Motor 2 applies periodic load modulation, and a TI C2000 controller executes a 500Hz loop with CAN communication. Data are streamed to a host PC for discrete-time LTP (DT-LTP) identification.

2. EXPERIMENTAL TEST BENCH ARCHITECTURE

This section presents the hardware and software architecture of the experimental platform developed for the generation of LTP datasets. The platform is designed to ensure deterministic timing, synchronized sensing, and direct access to motor-level signals, enabling controlled excitation of periodic dynamics and reproducible data acquisition for system identification purposes.

2.1 Electromechanical Architecture

The experimental test bench employs two coaxially aligned and rigidly coupled brushless servo actuators (CubeMars AK80-9), forming a motor-motor assembly supported by custom intermediate mounting components. One actuator is designated as the input motor (Motor 1), while the second operates as the load motor (Motor 2). Due to the rigid mechanical coupling, both actuators exhibit identical angular velocity ($\dot{\theta}$) and angular acceleration ($\ddot{\theta}$). By eliminating significant shaft compliance and misalignment effects, the rigid coupling promotes consistent and repeatable periodic excitation. The motors are powered by a 24 V DC voltage source. Each motor provides absolute encoder-based measurements, including position, velocity, and torque- related feedback, which can be utilized for closed-loop control and dataset recording.

To enable low-level access to motor signals, a TI C2000-class microcontroller development board (LAUNCHXL-F28379D) is employed for real-time control and data acquisition.

2.2 Embedded Software Architecture

In the software design, flexibility for dataset acquisition and rapid adaptation to new experimental scenarios were primary considerations. The actuators natively provide absolute encoder-based measurements, eliminating the need for additional sensing interfaces. Bidirectional communication is established over a CAN bus, where command inputs and multi-field feedback signals are exchanged using 8-byte frames in MIT mode. The CAN bus is terminated with 120 Ω resistors to ensure signal integrity.

As shown in Fig. 1, the system operates as a fixed-rate real-time loop at $F_s = 500\,\text{Hz}$. After initialization, MIT mode is enabled on both actuators, and the control loop executes periodically in a timer interrupt-driven manner. At each cycle, (i) a sinusoidal torque reference is applied to Motor 1 while encoder feedback is acquired, (ii) the torque command for Motor 2 is computed according to Section 3, and (iii) updated command frames are transmitted while measurement data are streamed. This structure ensures consistent sampling and synchronized logging.

Torque is commanded in newton-meters ($N \cdot m$) via the MIT protocol. Internally, the actuator employs Field Oriented Control (FOC), where the torque reference is mapped to a q-axis current, generating torque proportionally to motor current. The reported torque is an internally estimated value derived from phase current measurements rather than a direct sensor measurement. Position and velocity are obtained from the embedded 14-bit absolute encoder in radians (rad) and radians per second (rad/s), respectively.

For offline analysis, time-stamped measurement data are streamed to a host PC via the Serial Communication Interface (SCI) over USB. The transmitted signals include the torque reference and encoder-based measurements of angular velocity, position, and torque. Data are logged at $F_s = 500\,\text{Hz}$ and stored in CSV format for subsequent processing and system identification in MATLAB.

3. LTP DYNAMICS REALIZATION AND DATA ANALYSIS

3.1 LTP Dynamics via Periodic Feedback Modulation

This section explains how LTP system dynamics are achieved through the embedded firmware implementation. The control logic is structured around a periodic feedback modulation law designed to induce LTP behavior. By embedding a deterministic periodic component within the control loop, the firmware effectively imposes time-varying system coefficients, thereby generating LTP dynamics in the closed-loop system.

To induce LTP system dynamics characterized by a pumping frequency $f_0 = 2\,\text{Hz}$, one actuator is designated as the input motor (Motor 1) and is driven by a single-frequency sinusoidal torque command defined as

$$u_1(t) = A_{\text{in}}(5 + \sin(2\pi f_{\text{in}} t))\,. \tag{1}$$

where $A_{\text{in}} = 0.429$ and $f_{\text{in}} \in [0.1,\, 9.9]\,\text{Hz}$.

The other actuator serves as the load motor (Motor 2). LTP dynamics are induced by feeding back the angular velocity through a sinusoidally modulated feedback law:

$$u_2(t) = -\big(F_0 + F_1 \cos(2\pi f_0 t)\big)\dot{\theta}(t), \tag{2}$$

where $F_0 = 0.618$, $F_1 = 0.468$, and $f_0 = 2\,\text{Hz}$. The constant offset term in the input command, i.e., the addition of the +5 component in (1) and the - sign in (2), are introduced to establish a non-zero torque operating level for the coupled motor assembly. Without these modifications, the system would operate predominantly near zero velocity, where static friction and dead zone-like nonlinearities distort the waveform and introduce unintended harmonic content. The offset ensures sufficient excitation to overcome stiction and inertia, thereby producing smoother periodic motion. As shown in Fig. 2, the angular velocity trajectory exhibits continuous oscillatory behavior without pronounced sticking near zero crossings, and the corresponding frequency spectrum displays well-defined harmonic and sideband components without excessive broadband distortion Fig. 4. These observations confirm that the selected bias improves waveform regularity while preserving the intended LTP structure.

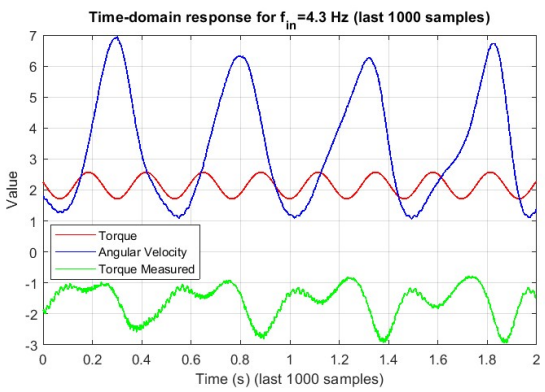


Fig. 2. Representative Single Run Time-domain response for $f_{\text{in}} = 4.3\,\text{Hz}$.

The parameters A_{in}, F_0, F_1 were determined empirically through repeated experimental trials. The tuning process was carried out considering not only closed-loop stability but also the mechanical characteristics of the rigidly coupled motor assembly, including thermal resistance and structural stiffness. Owing to the high mechanical rigidity of the setup, the system tolerates relatively strong periodic excitation without inducing excessive compliance-induced oscillations or instability. The selected parameter values therefore ensure stable closed-loop operation while maintaining sufficiently strong periodic modulation to induce observable LTP behavior without driving the actuators into saturation. As shown in Fig. 2 and Figs. 3-5, the selected parameter set produces smooth time-domain responses and clearly observable spectral components. This indicates that the excitation level is sufficient for frequency-domain analysis without introducing excessive oscillations or distortions in the measured response.

3.2 Data Curation and Spectral Analysis

For each excitation frequency in the range 0.1 Hz to 9.9 Hz data were recorded for 60 s. Excitation at 0.5 Hz and its integer multiples were excluded to avoid spectral overlapping between input harmonics and the pumping frequency. Such overlaps cause aliasing that prevents the unique decoupling of individual harmonic transfer functions, leading to numerical singularity and inconsistent identification results.

Following acquisition, a curation procedure was applied to convert raw log files into consistent datasets. Each file was parsed to extract time stamps, angular velocity, measured torque, and angular position signals. To analyze steady-state behavior, the final 20 s segment of each recording was selected, corresponding to 10,000 samples at a sampling frequency of $F_s = 500\,\text{Hz}$.

Frequency-domain analysis was subsequently performed using the Fast Fourier Transform (FFT) to examine harmonic content and sideband structure. The resulting spectra were used to verify the presence of LTP-induced frequency coupling and to assess spectral consistency across excitation frequencies.

Table 1. Observed angular velocity harmonic sideband components for different excitation frequencies ($f_0 = 2\,\text{Hz}$).

f_{in} (Hz)	Qty.	$k=0$	$k=+1$	$k=-1$	$k=+2$	$k=-2$
0.3	Freq.	0.3	2.3	-1.7	4.3	-3.7
	Mag.	0.360	0.129	0.134	0.041	0.045
4.3	Freq.	4.3	6.3	2.3	8.3	0.3
	Mag.	0.239	0.062	0.099	0.014	0.042
8.3	Freq.	8.3	10.3	6.3	12.3	4.3
	Mag.	0.175	0.029	0.049	0.004	0.015

To ensure identification consistency in our future works, raw data were trimmed to satisfy $T = nP + 1$ samples, where P is the pumping period. This ensures exactly n complete cycles and allows the identification algorithm to capture consistent periodic transitions. A phase-alignment procedure was then applied so that the pumping index $k \bmod P$ is identical across all experiments. Since the system matrices $A(k)$ and $B(k)$ depend on phase, any mismatch would mix different periodic states and lead to biased estimates. By enforcing a consistent phase index, each data point corresponds to the same point in the periodic cycle, preventing coefficient blurring and enabling accurate recovery of the time-varying dynamics. Without this step, the identified model would exhibit smoothed dynamics and reduced sensitivity to true periodic variations.

3.3 Experimental Demonstration of LTP Dynamics

The recorded signals are inspected in the frequency domain to verify the expected mixing behavior produced by (2). When the system is excited at f_{in}, the measured response exhibits spectral components at $f_{\text{in}} \pm k f_0$, where $f_0 = 2\,\text{Hz}$ and $k = 1, 2, 3, \ldots$, consistent with LTP frequency coupling. Representative spectra and time-domain responses for excitation frequencies 0.3, 4.3, and 8.3 Hz are shown in Figs. 3–5.

The spectra are obtained from steady-state portions of experimental runs. Selected experiments were repeated to confirm consistency. In the figures, 'Torque' denotes the commanded reference, 'Torque Measured' the internally estimated feedback, and 'Angular Velocity' the measured

rotor speed. Single-run spectra are shown without averaging.

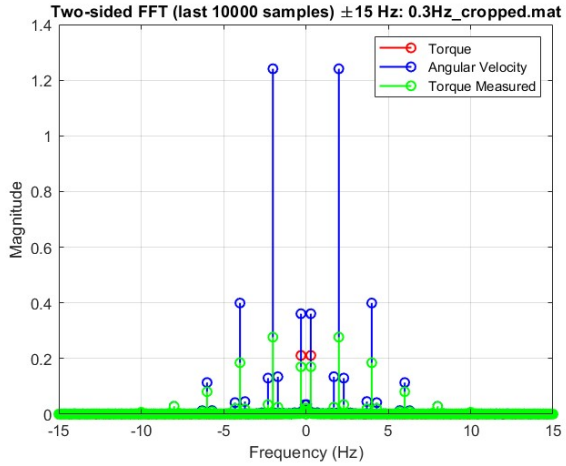


Fig. 3. Two-sided FFT response for $f_{\text{in}} = 0.3\,\text{Hz}$.

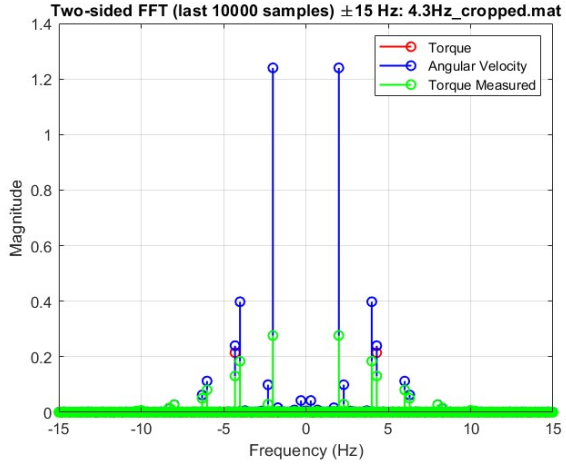


Fig. 4. Two-sided FFT response for $f_{\text{in}} = 4.3\,\text{Hz}$.

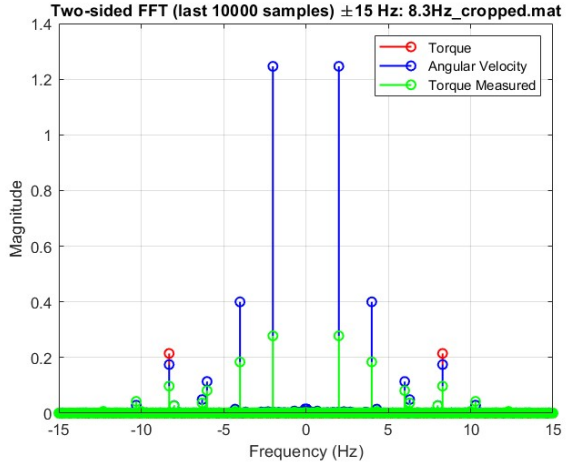


Fig. 5. Two-sided FFT response for $f_{\text{in}} = 8.3\,\text{Hz}$.

In each case, a dominant pumping component and symmetric sideband pairs are observed. Sideband magnitudes decrease with increasing harmonic order, indicating attenuation of higher-order effects. The corresponding angular velocity harmonic magnitudes are summarized in Table 1. The consistent spectral structure confirms that the periodic feedback modulation induces observable frequency coupling while preserving closed-loop stability, demonstrating the realization of LTP dynamics.

4. CONCLUSION

This paper presented an embedded coupled-motor platform for reproducible realization of Linear Time-Periodic (LTP) dynamics. Deterministic 500 Hz operation enabled synchronized acquisition and phase-consistent datasets suitable for system identification. Experiments exhibited clear sideband structures at $f_{\text{in}} \pm k f_0$, confirming successful realization of LTP behavior and providing a reliable platform for systematic investigation of LTP systems.

DECLARATION OF GENERATIVE AI USAGE

During the preparation of this work the authors used ChatGPT 5.2 in order to assist with language refinement, LaTeX formatting, code structuring, and improving the clarity and organization of technical descriptions. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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