

Xujun LYU, Long DI, Zongli LIN, 2019. On robustness of an AMB suspended energy storage flywheel platform under characteristic model based all-coefficient adaptive control laws. *Frontiers of Information Technology & Electronic Engineering*, 20(1):120-130. <https://doi.org/10.1631/FITEE.1800606>

On robustness of an AMB suspended energy storage flywheel platform under characteristic model based all-coefficient adaptive control laws

Key words: Intelligent control; Robustness; Uncertainty; Disturbance rejection; Active magnetic bearings; Energy storage flywheels

Corresponding author: Xujun LYU

E-mail: lyuxujun@mail.hzau.edu.cn

 ORCID: <https://orcid.org/0000-0002-2466-2338>

Motivation (1/5)

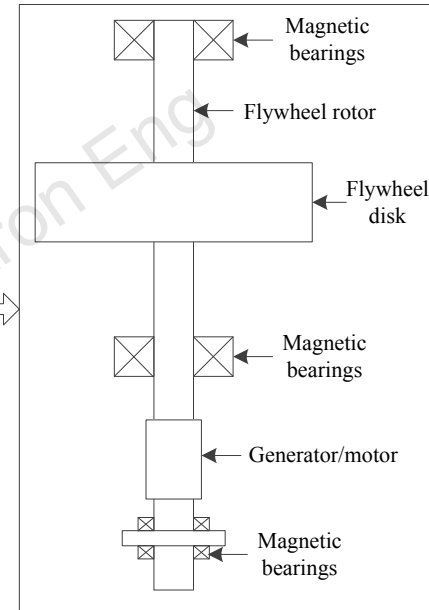
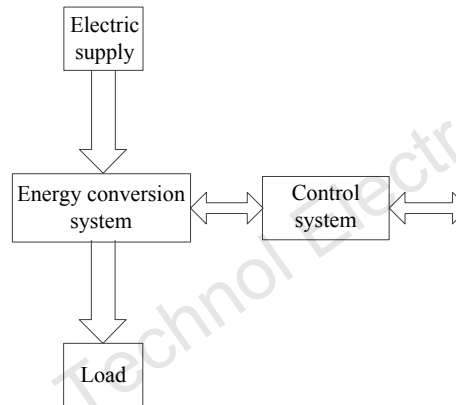
■ Flywheels

$$E = \frac{1}{2} J_p \omega^2$$

E : stored energy;

J_p : polar moment of inertia;

ω : angular speed.



■ Literature review

The complexity of AMB suspended flywheel systems

→ Test rigs

Too costly

The absence of past operational data

→ The implementation of control designs

Too difficult

We recently developed an experimental platform for AMB suspended energy storage flywheel in the Rotating Machinery and Controls (ROMAC) Laboratory, University of Virginia (Lyu, et al., 2016).

Motivation (2/5)

■ Literature review (Cont'd)

The classical PID control design method

→ Easy to implement but not effective in handling complex rotordynamics

Modern control theory (H_∞ and μ -synthesis)

→ Usually requires a plant model and an accurate characterization of the uncertainties

Di and Lin (2014) explored the application of characteristic model based all-coefficient adaptive control (ACAC), originally proposed by Wu et al. (2007, 2009).

→ Resulting in lower levels of vibration than that of a benchmark μ -synthesis controller

We implemented the characteristic model based all-coefficient adaptive control (ACAC) on the platform mentioned above (Lyu, et al., 2018). Despite its simplicity, the characteristic model based ACAC can achieve a strong control performance according to both simulation and experimental results.

Motivation (3/5)

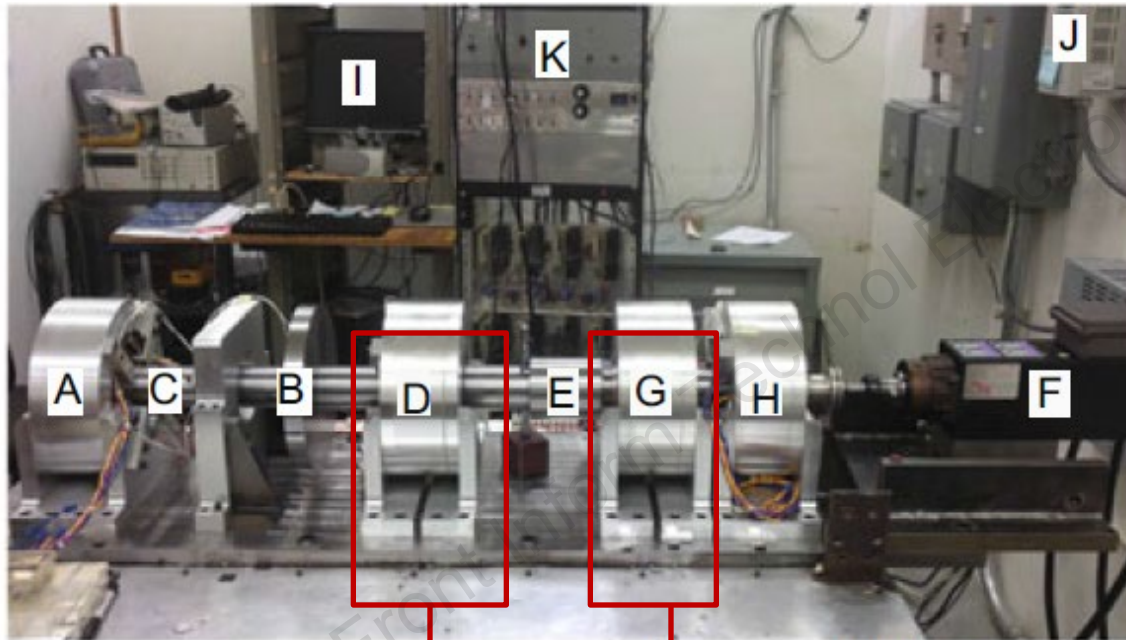
■ AMB suspended flywheel test rig

$$M\ddot{q} + (C + \Omega G)\dot{q} + Kq = B_m F_{\text{mag}} + B_e F_{\text{ext}}, \quad (1)$$

where M is the symmetric flywheel rotor mass matrix, C the symmetric damping matrix, G the skew-symmetric gyroscopic effect matrix, K the symmetric stiffness matrix, Ω the rotational speed, B_m the position distribution matrix of the support AMBs, F_{mag} the forces provided by support AMBs, B_e the position distribution matrix of the external forces, F_{ext} the external forces acting on the rotor, and q the generalized displacement vector.

Motivation (4/5)

■ AMB suspended flywheel test rig (Cont'd)



- | | |
|---|-----------------------------|
| A: non-driven end support AMB | B: gyroscopic disk 1 |
| C: rotor shaft | D: mid-span disturbance AMB |
| E: gyroscopic disk 2 | F: electric motor |
| G: quarter-span disturbance AMB | H: driven end support AMB |
| I: control station | J: variable frequency drive |
| K: amplifiers and sensor conditioning station | |

To emulate the operation of an energy storage flywheel

Fig. 1 A flexible rotor-AMB test rig

Motivation (5/5)

■ AMB suspended flywheel test rig (Cont'd)

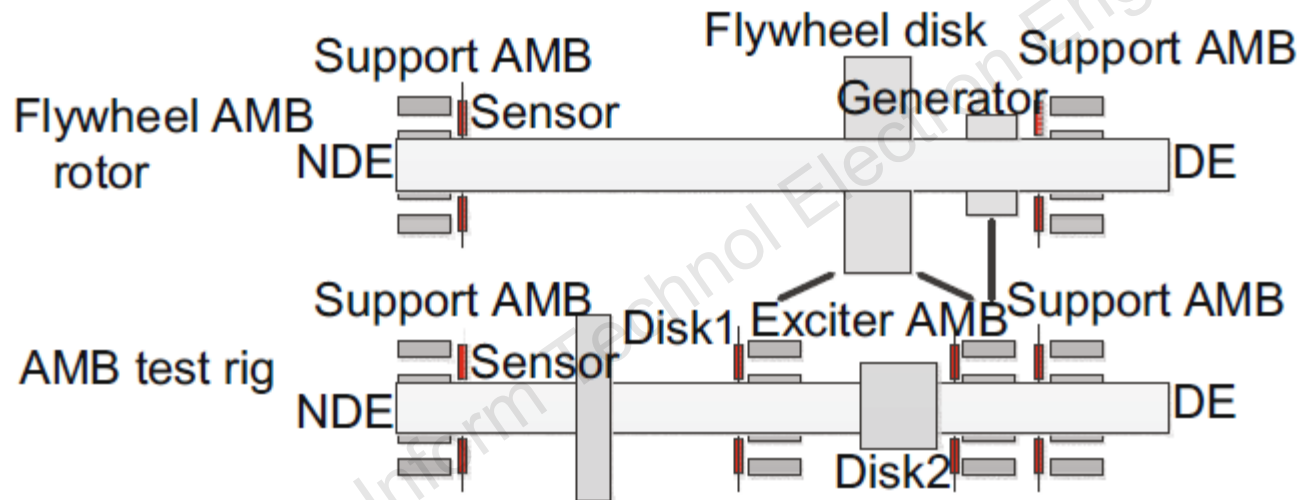


Fig. 2 Schematic of the experimental platform for AMB suspended flywheels

The exciter AMB at the quarter span

→ To emulate the negative stiffness induced by the generator

Two exciter AMBs at the mid-span and the quarter-span

→ To generate gyroscopic coupling resulting from the flywheel disk

Main idea

To examine the robustness of the characteristic model based ACAC on the AMB suspended energy storage flywheel platform with respect to:

1. plant uncertainties;
2. external disturbances;
3. time delay.

Method (1/3)

■ The characteristic model based ACAC

Overview of the closed-loop system:

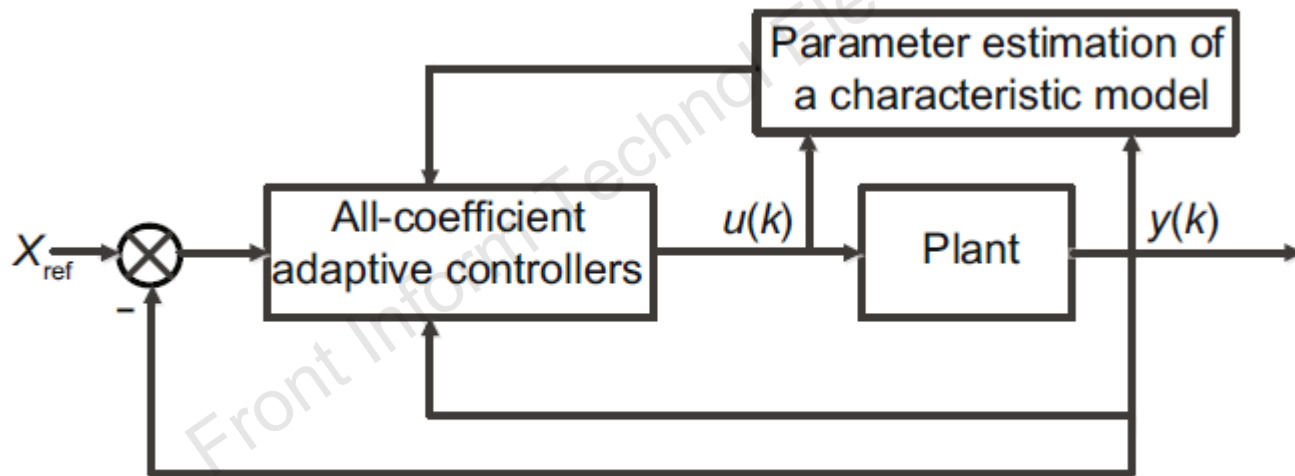


Fig. 3 Diagram of the characteristic model based ACAC system

Method (2/3)

■ The characteristic model based ACAC (Cont'd)

Characteristic modeling:

Considering a linear time-invariant plant described as

$$G(s) = \frac{b_m s^m + b_{m-1} s^{m-1} + \dots + b_1 s + b_0}{s^n + a_{n-1} s^{n-1} + \dots + a_1 s + a_0},$$

If the control objective is position keeping or reference tracking, and the sampling period T is sufficiently small

$$\begin{aligned} y(k) = & f_1(k)y(k-1) + f_2(k)y(k-2) \\ & + g_0(k)u(k-1) + g_1(k)u(k-2), \end{aligned} \quad (3)$$

where $u(k)$ is the control input, $y(k)$ the system output, and $f_1(k)$, $f_2(k)$, $g_0(k)$, and $g_1(k)$ the characteristic parameters

Method (3/3)

■ The characteristic model based ACAC (Cont'd)

The controller

$$u_c(k) = u_O(k) + u_G(k) + u_D(k) + u_I(k),$$

Maintaining/tracking control

$$u_O(k) = \frac{y_r(k) - \hat{f}_1(k)y(k) - \hat{f}_2(k)y(k-1) - \hat{g}_1(k)u_O(k-1)}{\hat{g}_0(k) + \lambda_1},$$

:

Golden section adaptive control

$$u_G(k) = \frac{l_1 \hat{f}_1(k)\tilde{y}(k) + l_2 \hat{f}_2(k)\tilde{y}(k-1) + \hat{g}_1(k)u_G(k-1)}{\hat{g}_0(k) + \lambda_1},$$

:

Differential control:

$$u_D(k) = d_1 \frac{\tilde{y}(k) - \tilde{y}(k-1)}{T},$$

Integral control:

$$u_I(k) = d_1 \frac{\tilde{y}(k) - \tilde{y}(k-1)}{T},$$

where $y_r(k)$ is the reference output, λ_1 is a positive constant, $\tilde{y}(k) = y_r(k) - y(k)$, $l_1 = 0.382$, $l_2 = 0.618$, and d_1 and d_2 are positive constants.

Major results (1/11)

■ Review of simulation results

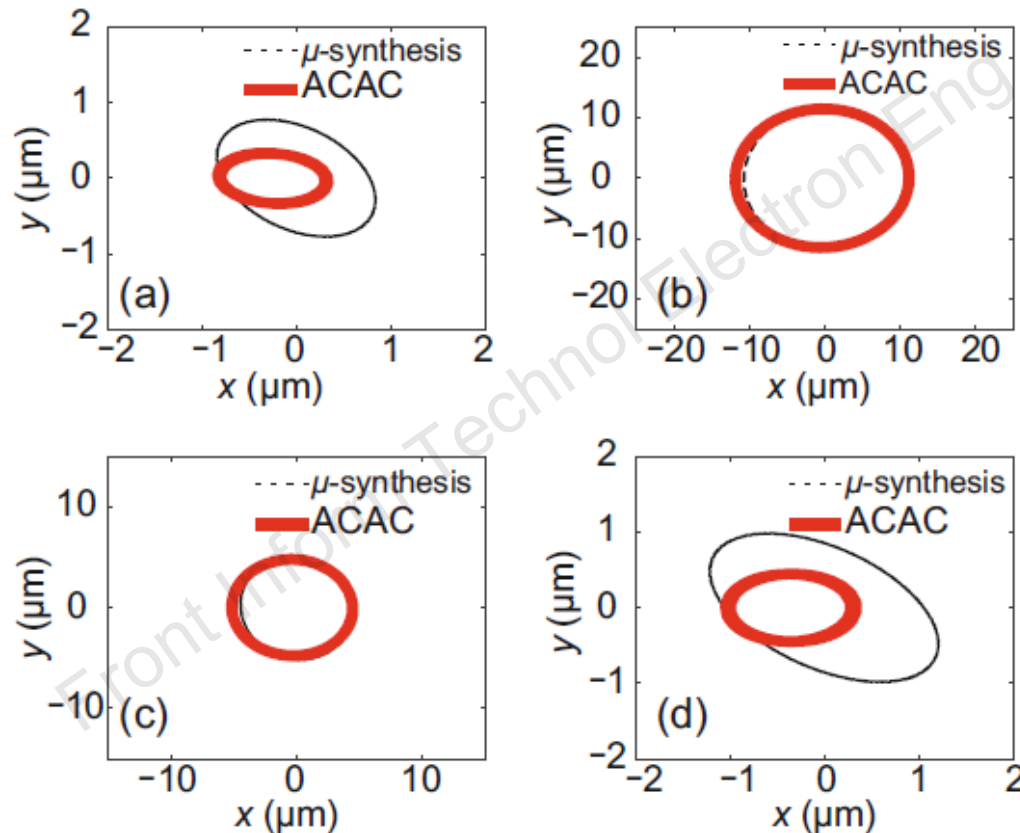


Fig. 4 Simulated rotor orbits at $\Omega = 7600 \text{ r/min}$ under the μ -synthesis controller and characteristic model based ACAC: (a) $dnx-dny$; (b) $dm x-dm y$; (c) $dq x-dq y$; (d) $ddx-ddy$

Major results (2/11)

■ Review of experimental results

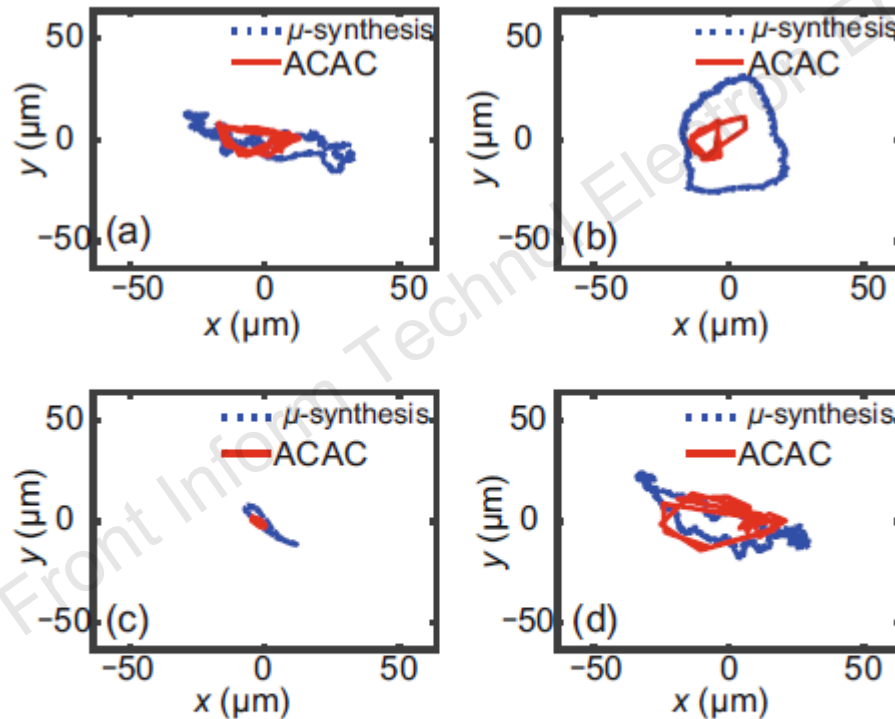


Fig. 5 Experimental rotor orbits at $\Omega = 7600$ r/min under the μ -synthesis controller and characteristic model based ACAC: (a) dn_x-dn_y ; (b) dm_x-dm_y ; (c) dq_x-dq_y ; (d) dd_x-dd_y

Major results (3/11)

■ Robustness with respect to plant uncertainties

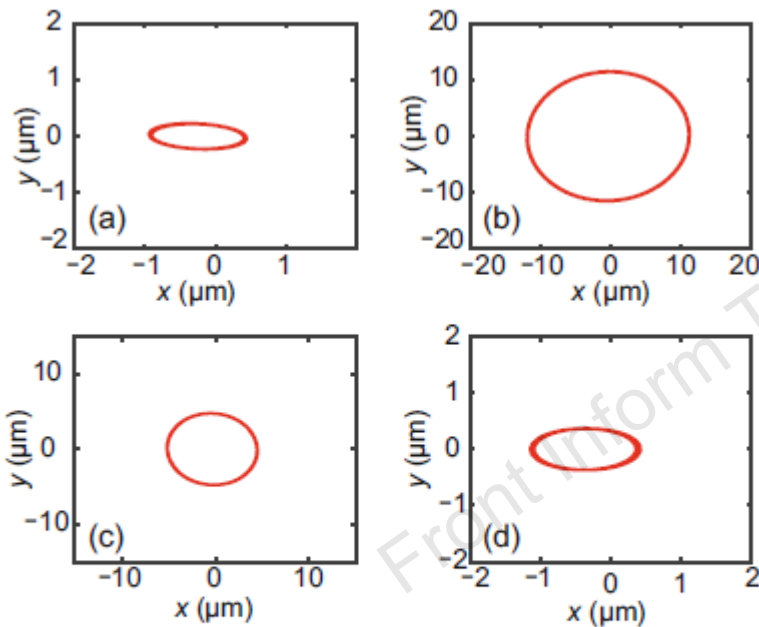


Fig. 6 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.042$ kg·m² under characteristic model based ACAC laws: (a) $dn̄x-dn̄y$; (b) $dm̄x-dm̄y$; (c) $dq̄x-dq̄y$; (d) $dd̄x-dd̄y$

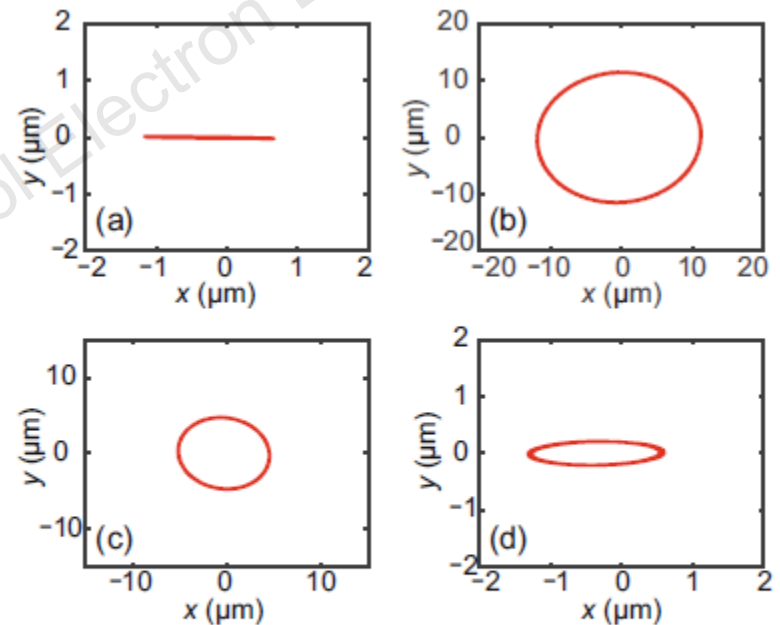


Fig. 7 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.084$ kg·m² under characteristic model based ACAC laws: (a) $dn̄x-dn̄y$; (b) $dm̄x-dm̄y$; (c) $dq̄x-dq̄y$; (d) $dd̄x-dd̄y$

Major results (4/11)

■ Robustness with respect to plant uncertainties

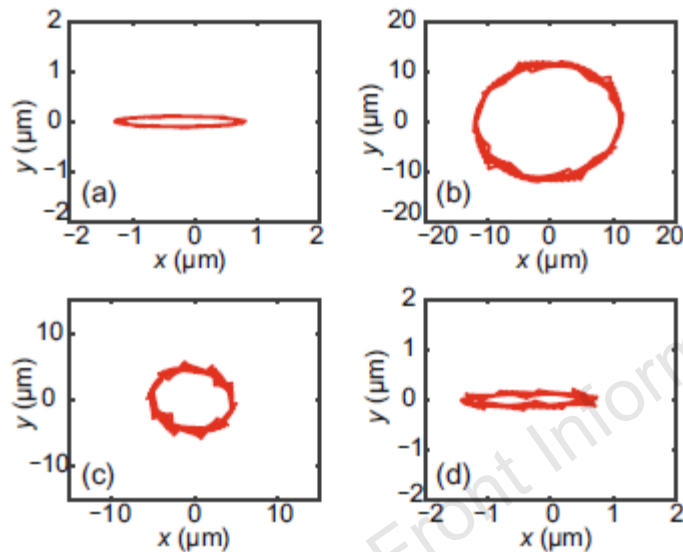


Fig. 8 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.105$ kg·m² under characteristic model based ACAC laws: (a) dn_x-dn_y ; (b) dm_x-dm_y ; (c) dq_x-dq_y ; (d) dd_x-dd_y

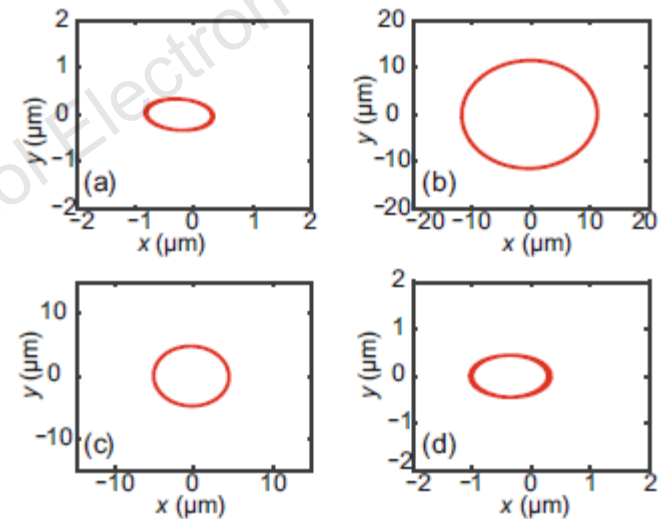


Fig. 9 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² under characteristic model based ACAC laws: (a) dn_x-dn_y ; (b) dm_x-dm_y ; (c) dq_x-dq_y ; (d) dd_x-dd_y

Major results (5/11)

■ Robustness with respect to external disturbances

Constant disturbances:

Table 1 Peak values of the rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.1, 0.3$, and 0.5 A, under characteristic model based ACAC laws

Location	Peak value (μm)		
	$\Delta i = 0.1$ A	$\Delta i = 0.3$ A	$\Delta i = 0.5$ A
dnx	25	74	122
dny	42	124	207
dmx	41	95	152
dmy	45	110	176
dqx	37	98	159
dqy	31	84	137
ddx	33	98	162
ddy	25	73	121

Major results (6/11)

■ Robustness with respect to external disturbances

Constant disturbances:

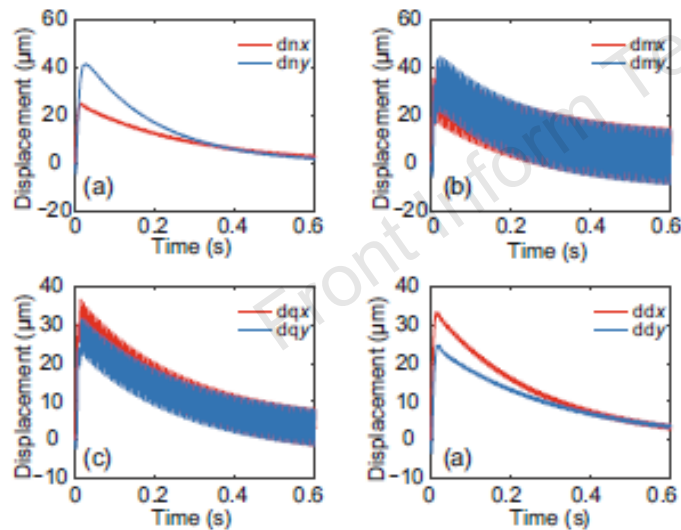


Fig. 10 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.1$ A, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

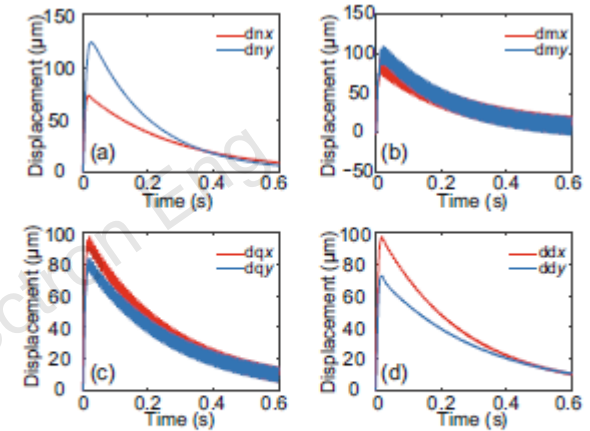


Fig. 11 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.3$ A, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

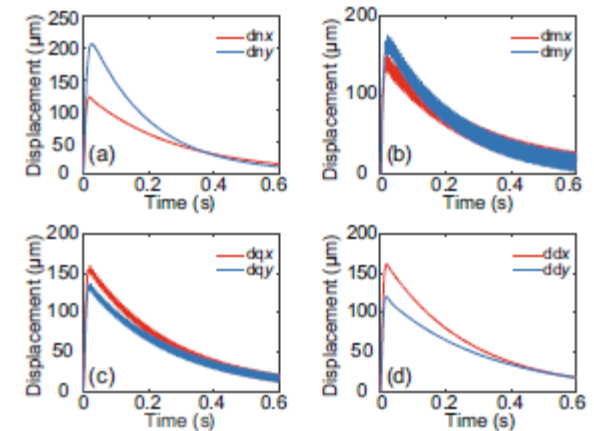


Fig. 12 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.5$ A, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

Major results (7/11)

■ Robustness with respect to external disturbances

Constant disturbances:

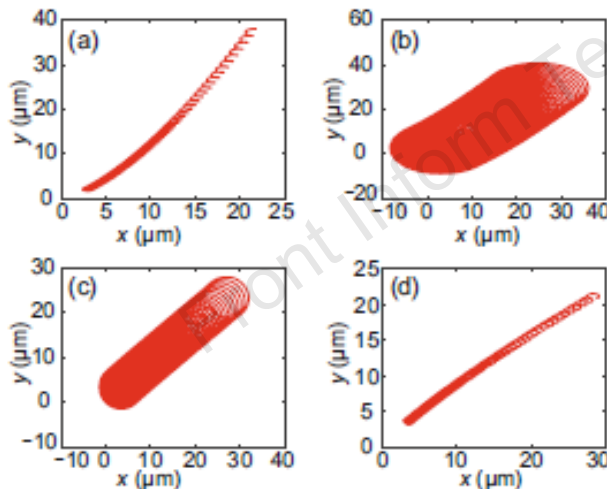


Fig. 13 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.1$ A, under characteristic model based ACAC laws: (a) $dnz-dny$; (b) $dmz-dmy$; (c) $dqz-dqy$; (d) $ddz-ddy$

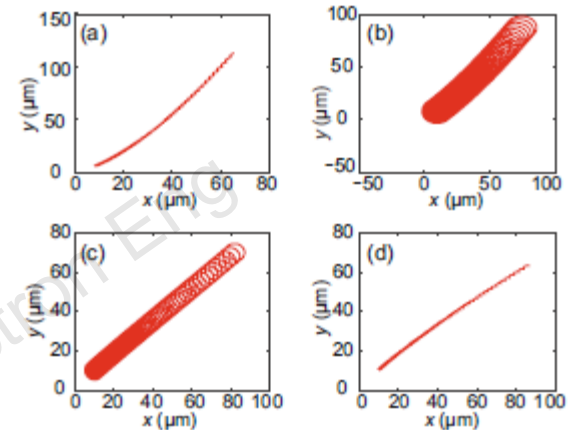


Fig. 14 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.3$ A, under characteristic model based ACAC laws: (a) $dnz-dny$; (b) $dmz-dmy$; (c) $dqz-dqy$; (d) $ddz-ddy$

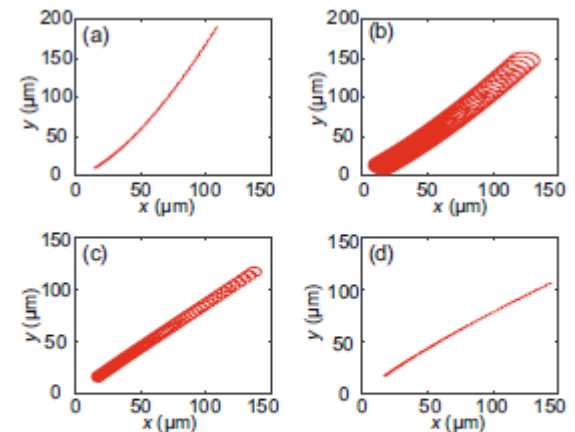


Fig. 15 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.5$ A, under characteristic model based ACAC laws: (a) $dnz-dny$; (b) $dmz-dmy$; (c) $dqz-dqy$; (d) $ddz-ddy$

Major results (8/11)

■ Robustness with respect to external disturbances

Sinusoidal disturbances:

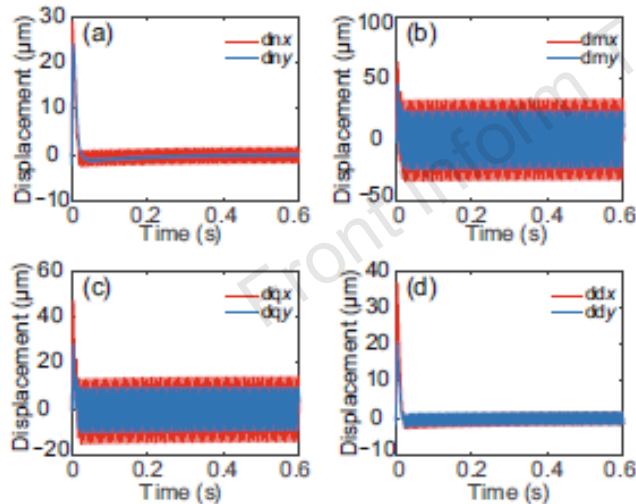


Fig. 16 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.5\sin(\omega t)$, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

Table 2 Peak values of the rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.5\sin(\omega t)$, under characteristic model based ACAC laws

Location	Peak value (μm)
dnx	29.1
dny	24.2
dmx	63.2
dmy	45.3
dqx	47.2
dqy	28.1
ddx	37.0
ddy	20.5

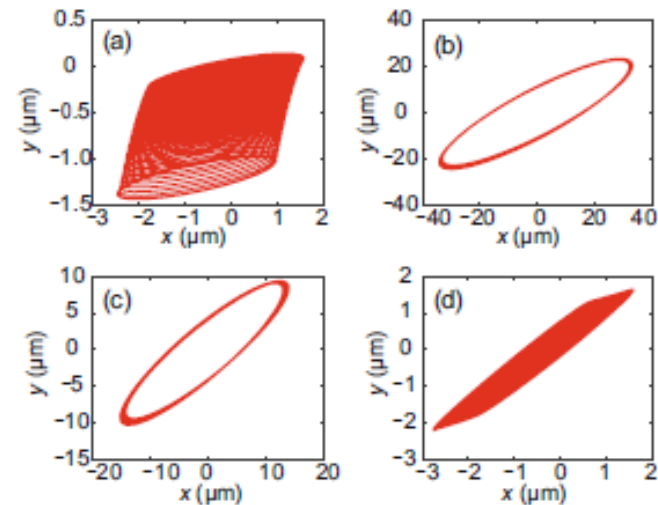


Fig. 17 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m² and $\Delta i = 0.5\sin(\omega t)$, under characteristic model based ACAC laws: (a) dnx-dny; (b) dmrx-dmy; (c) dqx-dqy; (d) ddx-ddy

Major results (9/11)

■ Robustness with respect to time delays

Control input delays:

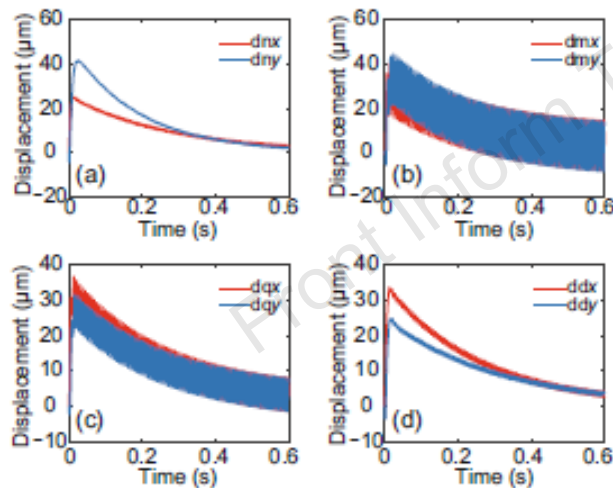


Fig. 18 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and control input delay $\tau = T_s$, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

Table 3 Peak values of the rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and control input delay $\tau = T_s$, under characteristic model based ACAC laws

Location	Peak value (μm)
dnx	25.2
dny	41.7
dmx	41.1
dmy	44.5
dqx	36.8
dqy	31.6
ddx	33.7
ddy	24.8

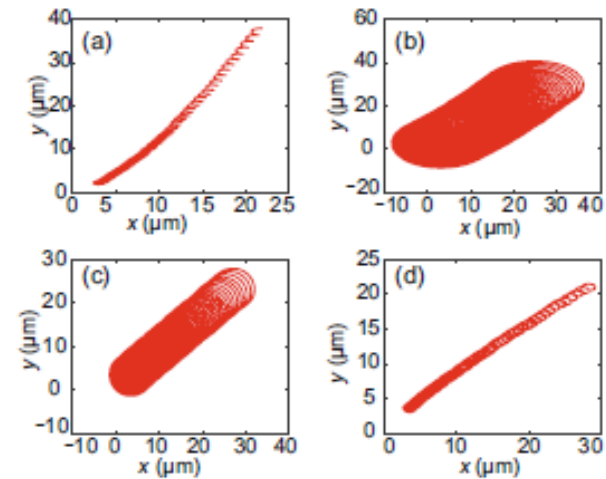


Fig. 19 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and control input delay $\tau = T_s$, under characteristic model based ACAC laws: (a) dnx-dny; (b) dmx-dmy; (c) dqx-dqy; (d) ddx-ddy

Major results (10/11)

■ Robustness with respect to time delays

Sensor output delays:

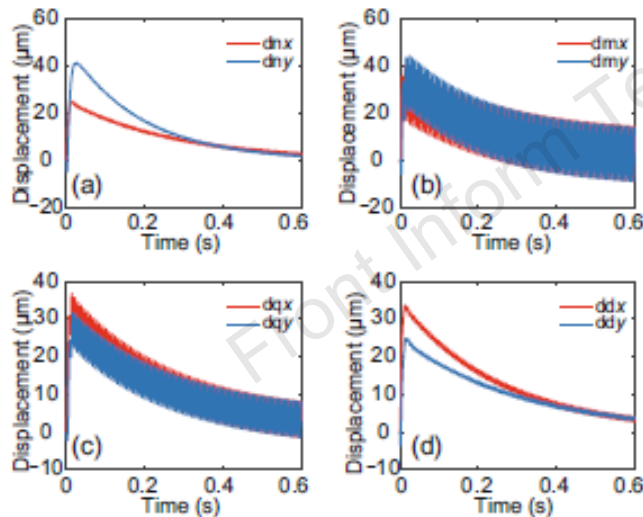


Fig. 20 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

Table 4 Peak values of the rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws

Location	Peak value (μm)
dnx	25.3
dny	41.8
dm̄x	41.1
dm̄y	44.3
dq̄x	36.8
dq̄y	31.6
dd̄x	33.7
dd̄y	24.8

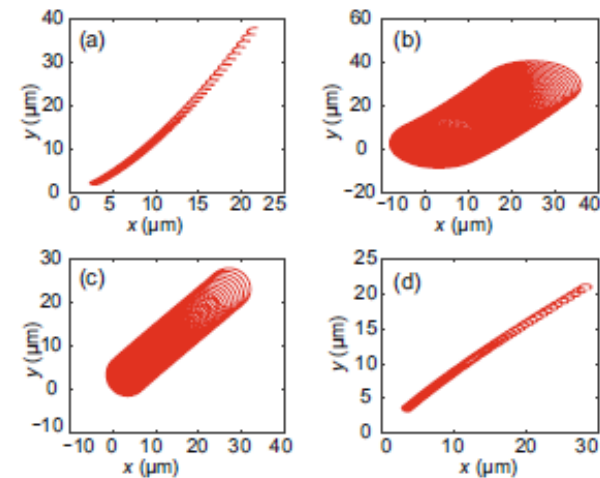


Fig. 21 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws: (a) dnx-dny; (b) dm̄x-dm̄y; (c) dq̄x-dq̄y; (d) dd̄x-dd̄y

Major results (11/11)

■ Robustness with respect to time delays

Delays at control inputs and sensor outputs:

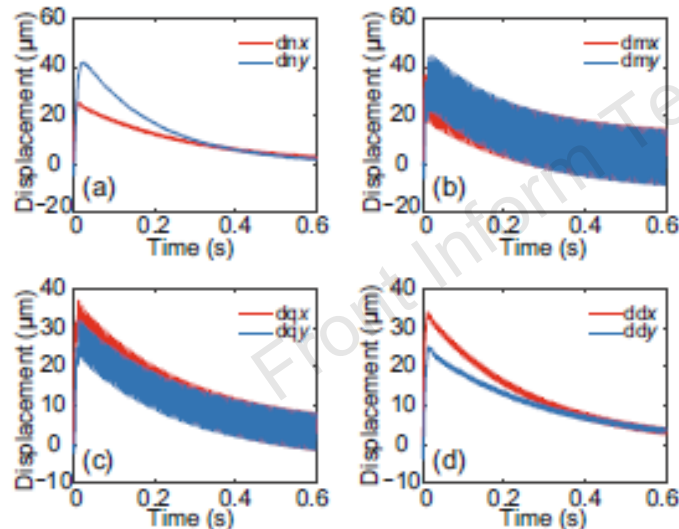


Fig. 22 Rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, control input delay $\tau = T_s$, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws: (a) NDE; (b) MID; (c) QTR; (d) DE

Table 5 Peak values of the rotor displacements at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, control input delay $\tau = T_s$, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws

Location	Peak value (μm)
dnx	25.3
dny	41.8
dmx	41.4
dmy	44.6
dqx	36.9
dqy	31.8
ddx	34.0
ddy	25.1

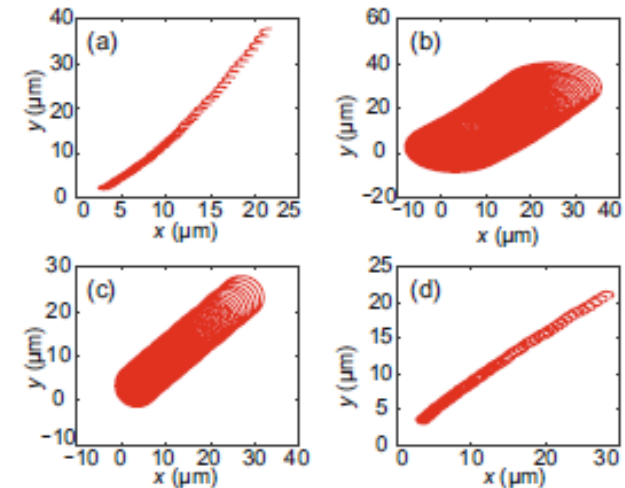


Fig. 23 Rotor orbits at $\Omega = 7600$ r/min of an emulated flywheel with $J_p = 0.021$ kg·m², $\Delta i = 0.1$ A, control input delay $\tau = T_s$, and sensor output delay $\tau = T_s$, under characteristic model based ACAC laws: (a) dnx-dny; (b) dmx-dmy; (c) dqx-dqy; (d) ddx-ddy

Conclusions

1. The robustness of the characteristic model based all-coefficient adaptive control (ACAC) on an AMB suspended energy storage flywheel test rig with respect to plant uncertainties, external disturbances, and time delay is investigated.
2. The experimental platform for the AMB suspended energy storage flywheel, developed from an existing flexible rotor-AMB test rig in the ROMAC Laboratory at the University of Virginia, has been reviewed.
3. The rotor behaviors of the flywheel emulation platform under the characteristic model based ACAC have been briefly presented.
4. The performances of the closed-loop flywheel AMB systems with plant uncertainties, external disturbances, and time delay have been tested in the simulations.
5. Extensive and systematic simulations demonstrated that the characteristic model based ACAC possesses considerable robustness with respect to plant uncertainties, external disturbances, and time delay.

References

- Di L, Lin ZL, 2014. Control of a flexible rotor active magnetic bearing test rig: a characteristic model based all-coefficient adaptive control approach. *Contr Theor Technol*, 12(1):1-12. <https://doi.org/10.1007/s11768-014-0184-0>
- Lyu XJ, Di L, Yoon SY, et al., 2016. A platform for analysis and control design: emulation of energy storage flywheels on a rotor-AMB test rig. *Mechatronics*, 33:146-160. <https://doi.org/10.1016/j.mechatronics.2015.12.007>
- Lyu XJ, Di L, Lin ZL, et al., 2018. Characteristic model based all-coefficient adaptive control of an AMB suspended energy storage flywheel test rig. *Sci China Inform Sci*, 61(11):112204. <https://doi.org/10.1007/s11432-017-9327-0>
- Wu HX, Hu J, Xie YC, 2007. Characteristic model-based all-coefficient adaptive control method and its applications. *IEEE Trans Syst Man Cybern Part C (Appl Rev)*, 37(2):213-221. <https://doi.org/10.1109/TSMCC.2006.887004>
- Wu HX, Hu J, Xie YC, 2009. Characteristic Model-Based and Intelligent Adaptive Control. Science and Technology Press of China, Beijing, China (in Chinese).