

Fig. 7. Experiment validation of tracking trajectory of hub angle 1 using PSO

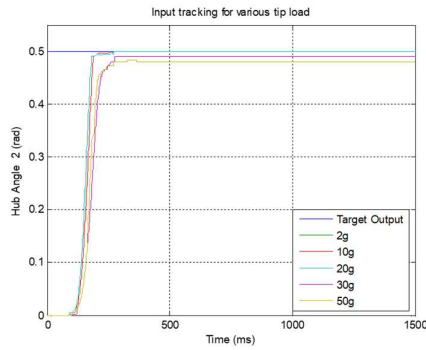


Fig. 8. Experiment validation of tracking trajectory of hub angle 2 using PSO.

The performance of hub angle response has precisely tracked the input motion up to 20 g. However, the link could not reach the desired output when the mass payload added is more than 20 g. The time responses of hub angles have shown significant changes whereby the system exhibits higher rise time and settling times with increasing payload. The results were more noticeable in link 2. This happened due to the first link failure to reach the desired output, thus the second link performance also gets affected. The results show that the link 2 was very much influenced by link 1. Therefore, it can be concluded the performance of fixed controller is limited whereby it is able to control up to certain payloads only.

Fig. 9 (a) - (e) illustrate the end-point acceleration response with the variations of payload for both link 1 and 2.

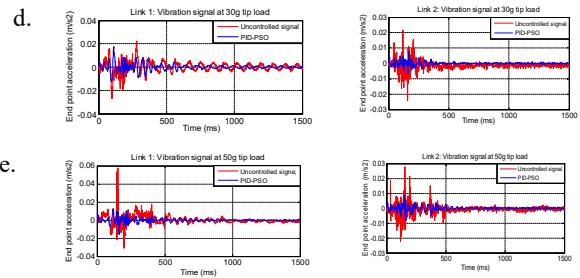
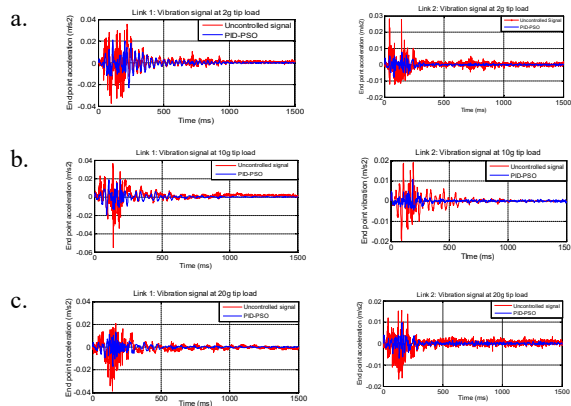


Fig. 9. Vibration suppression with variation of payload

It is noted that payload attached at the end effector has increased the total mass of the system. The flexibility of the link reduces as the payload increases. Hence, the increasing mass has significant effect on the performance of controller since the dynamic model of the system may change. From Fig. 5.43, it can be observed that the maximum disturbance magnitude is reduced as the weight of load is increased. This is due to the mass payload that compensated for the vibration overshoot. At 2 g, 10 g and 20 g loads attached, the vibration signal was found to have almost zero acceleration towards the end of observations. Meanwhile, it is observed that the amplitude vibration for 30 g yet to settle even after 15 s. The disturbance takes longer time to settle down as higher persistent oscillations can be seen with increased mass payload attached. The condition applies for both links. However, the pattern of the amplitude vibration for the mass payload at 50 g follows the first 3 payloads. This pattern may be due to the contribution of the mass payload at 50 g as a passive damper which increases the suppression level.

VI. CONCLUSION

The simulation studies showed that PID tuned by PSO offer good transient response. However, the experimental results indicate that the intelligent PID controller has their limitation when the payload exist in the system. The performance of the controller reduces when the payload increases more than 20 g. In the real application, this finding is crucial to estimates the presence of uncertainty in the controllers. Notably, the controllers are fit to be used in real application subjected to how the tuning process is carried out in the system. It is advisable and practical to tune the controllers with the presence of the maximum payload in the system.

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REFERENCES

- [1] M. Y. Abdullah, M. Hussein, M. Z. Md Zain, R. Ahmad, and R. Ganesh, "Effect of transducer mass on thin plate vibration," *Proc. - Int. Symp. Inf. Technol. 2008, ITSIM*, vol. 3, pp. 1–7, 2008, doi: 10.1109/ITSIM.2008.4631956.
- [2] A. Agyei-Agyemang and P. Akangah, "Optimisation of Plate Thickness Using Finite Difference Method," *J. Sci. Technol.*, vol. 28, no. 3, pp. 135–139, 2009, doi: 10.4314/just.v28i3.33114.
- [3] M. Z. Zakaria, M. S. Mohd Saad, H. Jamaluddin, and R. Ahmad, "Dynamic System Modeling of Flexible Beam System Using Multi-Objective Optimization Differential Evolution Algorithm," *Appl.*

- Mech. Mater.*, vol. 695, pp. 605–608, 2014, doi: 10.4028/www.scientific.net/amm.695.605.
- [4] I. Z. M. Darus and A. A. M. Al-Khafaji, “Non-parametric modelling of a rectangular flexible plate structure,” *Eng. Appl. Artif. Intell.*, vol. 25, no. 1, pp. 94–106, 2012, doi: 10.1016/j.engappai.2011.09.009.
- [5] Y. Xie, T. Zhao, and G. Cai, “Dynamic modeling and active control of flexible plate based on the input-output data,” *Acta Mech. Solida Sin.*, vol. 26, no. 3, pp. 255–262, 2013, doi: 10.1016/S0894-9166(13)60024-5.
- [6] I. Z. M. Darus, T. A. Zahidi Rahman, and M. Mailah, “Experimental evaluation of active force vibration control of a flexible structure using smart material,” *Int. Rev. Mech. Eng.*, vol. 5, no. 6, pp. 1088–1094, 2011.
- [7] M. S. Saad, H. Jamaluddin, I. Z. M. Darus, and I. A. Rahim, “Experimental study of active vibration control of a flexible beam system using iterative learning algorithm,” *Key Eng. Mater.*, vol. 660, pp. 356–360, 2015, doi: 10.4028/www.scientific.net/KEM.660.356.
- [8] F. Vázquez and F. Morilla, *Tuning decentralized pid controllers for MIMO systems with decouplers*, vol. 15, no. 1. IFAC, 2002.
- [9] H. P. Huang, J. C. Jeng, C. H. Chiang, and W. Pan, “A direct method for multi-loop PI/PID controller design,” *J. Process Control*, vol. 13, no. 8, pp. 769–786, 2003, doi: 10.1016/S0959-1524(03)00009-X.
- [10] R. M. Mahamood, “Direct adaptive hybrid Pd-Pid controller for two-link flexible robotic manipulator,” *Lect. Notes Eng. Comput. Sci.*, vol. 2, pp. 1127–1132, 2012.
- [11] R. M. Mahamood and J. O. Pedro, “Hybrid PD-PID with Iterative Learning Control for Two-Link Flexible Manipulator,” *Lect. Notes Eng. Comput. Sci.*, vol. 2194, no. 1, pp. 966–971, 2011.
- [12] Z. Mohamed, M. Khairudin, A. R. Husain, and B. Subudhi, “Linear matrix inequality-based robust proportional derivative control of a two-link flexible manipulator,” *JVC/Journal Vib. Control*, vol. 22, no. 5, pp. 1244–1256, 2016, doi: 10.1177/1077546314536427.
- [13] G. Leena and G. Ray, “A set of decentralized PID controllers for an n-link robot manipulator,” *Sadhana - Acad. Proc. Eng. Sci.*, vol. 37, no. 3, pp. 405–423, 2012, doi: 10.1007/s12046-012-0082-4.
- [14] M. Khairudin, . Sudiyatno, and F. Arifin, “NN robust based-PID Control of A Two-Link Flexible Robot Manipulator,” *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 2, no. 1, p. 7, 2012, doi: 10.18517/ijaseit.2.1.144.
- [15] J. Annisa, I. Z. Mat Darus, M. O. Tokhi, and S. Mohamaddan, “Implementation of PID Based Controller Tuned by Evolutionary Algorithm for Double Link Flexible Robotic Manipulator,” *2018 Int. Conf. Comput. Approach Smart Syst. Des. Appl. ICASSDA 2018*, pp. 1–5, 2018, doi: 10.1109/ICASSDA.2018.8477615.
- [16] A. Jamali and I. Z. Mat Darus, 2020 J. Phys: Conf. Ser. 1500 012020
- [17] M. A. Fadil, N. A. Jalil, and I. Z. M. Darus, “Intelligent PID Controller Using Iterative Learning Algorithm for Active Vibration Controller of Flexible Beam,” no. 4, pp. 80–85, 2013.
- [18] I. B. Tijani, R. Akmeliawati, A. G. A. Muthalif, and A. Legowo, “Optimization of PID controller for Flexible link system using a Pareto-based Multi-Objective differential (PMODE) evolution,” no. May, pp. 17–19, 2011.
- [19] H. Supriyono, M. O. Tokhi, and B. A. Md Zain, “Control of a single-link flexible manipulator using improved bacterial foraging algorithm,” *ICOS 2010 - 2010 IEEE Conf. Open Syst.*, no. Icos, pp. 68–73, 2010, doi: 10.1109/ICOS.2010.5720066.
- [20] A. A. Fahmy, M. Kalyoncu, and M. Castellani, “Automatic design of control systems for robot manipulators using the bees algorithm,” *Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng.*, vol. 226, no. 4, pp. 497–508, 2012, doi: 10.1177/0959651811425312.
- [21] H. M. Yatim and I. Z. Mat Darus, “Self-tuning active vibration controller using particle swarm optimization for flexible manipulator system,” *WSEAS Trans. Syst. Control*, vol. 9, no. 1, pp. 55–66, 2014.
- [22] I. Z. M. Darus and E. Otokhisheffieldadac, “Parametric and Non-Parametric Identification of a Two Dimensional Flexible Structure,” vol. 25, no. 2, pp. 119–143, 2006.
- [23] J. Annisa, I.Z. Mat Darus1, M.O. Tokhi, P. P. Mohd Samin (2018). Intelligent Modeling of Double Link Flexible Robotic Manipulator Using Artificial Neural Network, Journal of Vibroengineering (Vol. 20, Issue 3), ISSN Print 1392-8716.
- [24] A. Jamali, A. Z. Abidin, I. Z. Mat Darus, and M. Tokhi, “Controlling the non-parametric modeling of Double Link Flexible Robotic Manipulator using Hybrid PID tuned by P-Type ILA”, *IJIE*, vol. 10, no. 7, Nov. 2018.