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Study of X-Pattern Crank-Activated 4-Bar Fast Return Mechanism for Flapping Actuation in Robo Drones

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ABSTRACT

The study of insect-inspired flapping robo drones is exciting and ongoing, but creating realistic artificial flapping robots that can effectively mimic insect flight is difficult due to the transmission mechanism's need for lightweight and minimal connecting components. The objective of this work was to create a system of constructing a flapping superstructure with the fewest feasible links. This is one of the two strokes where the fast return mechanism turns circular energy into a variable angled flapping motion (obtained through simulation results). We have simulated the displacement modifications of the forward and return stroke variation. also conducted a kinematic study of the design processes differences, finding that it is significantly faster than the advance stroke. It was also seen that one of its levers lagged behind the others when flapping because of poor boundary conditions. Modelling the suggested motor-driven flapping actuation system helps verify its structural analysis and determine if it is appropriate for use in micro air vehicle applications.

1. Introduction

Substantial progress has been achieved by various researchers in grasping the incredible flying consistency and manoeuvrability of hummingbirds and flapping-wing insects/flies. Insect flight is dependent upon that synchronicity of individual flapping wings. Because of the impressive flight technique involved in insects and birds, a number of researchers have discovered motivation in organic flight controls (for example: microbat, Yang's MAV, Bristol's PCR prototype, Yang's Golden Snitch) to discover functional and effective person built flying technologies [1-6]. The flapping wing

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operation provides the more maintainable coordination between the wings, whenever related to the available rotary and static wing types. possibly as its transmission energy is distributed across a greater chord, fluctuating from either a threshold of minimum thrust to enhance opposite extremes of said flapping inclination to a substantial quality in mid-stroke. The amazing feature of the flapped frameworks is that they are meant to be a versatile, effective, and dynamic oscillation mechanism. Earlier studies have shown that the movement duration of up and down flapping strokes in forward flight is not always symmetric. It has been established that such descending fluttering period of certain dragonfly could be 2.37 orders of magnitude larger than the ascending flapping period. Moreover, the duration part of manmade FWAV downward and upward cycle proportions is nearly identical, thus synchronous flapping techniques shall always be chosen. Ultimately, yaw events might be produced by employing the velocity differential implications for both up and down movements, despite the fact that the synchronous flapping movement also creates the majority of such thrust power, as per Hubisz [7], Alexander *et al.,* [8], and De Wagter *et al.,* [9]. Due to having synchronous flapping movements, even moderate electric actuated FWMAVs were capable of vertical take-off are occasionally reluctant attain controlled hovering. In addition, they periodically rely on the latent equilibrium provided by their system's extra dampers, which impact its flapping behaviour [10]. The insect-mimicable KUBeetle-S employs a 4-bar connector with just a pulley–string arrangement to produce clap & fling impacts during both side sweep fluctuations, resulting in increased lift. The bigger swing amplitude of flapping - wing and the heavier load carrying capability contributes to a greater lift and the longest flying endurance possible. In accordance with Thunder I, the concept merges the varied layout well with construction of the crank unit, with the difference that restraining frames are employed in place of sliders. To ensure constant flapping activity across both planes, a six-bar arrangement with 14 pivoted elements were employed, resulting in increased lift. A miniature imitating bird, having crank-rockers system is composed of simple, compliant parts. As a result of their flaps, the first and second spars of such flap would deflect more by modifying the camber shape along with mid-chord airspeed and so changing the lifting and thrusting rates. The compliant of the first-spar modifies the apparent wingspan across the flapping plane to ensure stabilities without harmonic distortion. Researchers witness the rise in average thrust brought on by better wing compliance arrangements [11-16]. The Saturn concept utilizes a revolving crank-shaft method with a thread actuated dual pully system. the crank is driven by an electric motor, with parallel lines connected to it and each regulating the swings of both the respective pulley design at its wing joint. The fluttering aspect distribution is periodical. however relative to the latching mechanism approach, the amplitude of the edge flow velocity is reduced considerably. Since the construction arrangement supports pitch mobility, including such rotational and twisting distributions, this became practical to handle all three pitch, roll, and yaw dimensions [17]. The configuration of rotorcraft's swashplate assisted to deliver data input into operators with a substantially reduced frequency band compared to flapping frequency. Throughout wing transmembrane camber inversion, the impact of flap strokes resulted in the greatest outcomes because of the extreme wing modelling approaches [17,18]. The significance both fluttering actuating and wing orientation towards lift generation is apparent in the mechanics of the aforementioned design concept. Due to the complexity of developing and producing lighter, more efficient, and smaller FWMAVs, an efficient construction approach is essential to getting a superior conclusion.

We present a motor-driven crank-controlled fast return mechanism design for flapping actuation of Micro Aerial Vehicle wings. Because of its rapid comeback qualities, the ratio between both strokes differs. As a consequence, investigations and computational methods of flapping properties have substantiated proposed approach. Process factors analysed throughout simulated results include of flapping intensities, flap angles, angular speed, angular acceleration, torque, and force applied on the system architecture. Additionally, improper boundary conditions resulted in lag in one of its levers during flapping. The proposed motor-driven flapping actuation mechanism is structurally analysed and validated to ascertain its suitability for micro aerial vehicle applications.

2. Concept of Flapping Mechanism

Typically, a sliding attachment with crank is a 4-bar coupling system that includes 3R (joints with revolute motion) and one 1P (sliding/prismatic-joint), and has been utilized frequently in applications involving flapping wing aerial vehicles [19]. In any FWMAV, the rotation of the crank drives the linear movement/ sliding, which generates downward and upward strokes at the levers. There are two primary kinds of slider-cranks: in-line and offset. In an in-line configuration, the slider is positioned so that the line of passage of the slider's hinge joint follows the supply joint of the crank.

For example, because the crank rotates, a symmetrical linear motion of the slider is produced in both opposite directions. In a slider with an offset configuration, the axis of passage of such slider's rigid frame doesn't really travel through crank's primary pivot, resulting in a lopsided action. However, its speed in reverse is greater than its speed in forward travel. This is called a rapid return technique. Numerous additional design processes have revealed variances or latencies in the wing inclination trajectory of the both side wings [20]. By using slider crank technique as a basis, the authors developed a unique process consisting of two levers paired in a cross-x pattern, which is operated by a crank motor drive, as shown in Figure 1. In this instance, the fundamental architecture for transforming rotational movement to regulated angular flapping movement is indeed the X-shaped arrangement of two rapid return processes. As seen in Figure 1, this distinctive configuration of the rapid return technique is referred to as the main design concern. The critical elements of the concept of the flapping configurations are best illustrated using Figure 1, which was created using CAD program through Fusion 360.

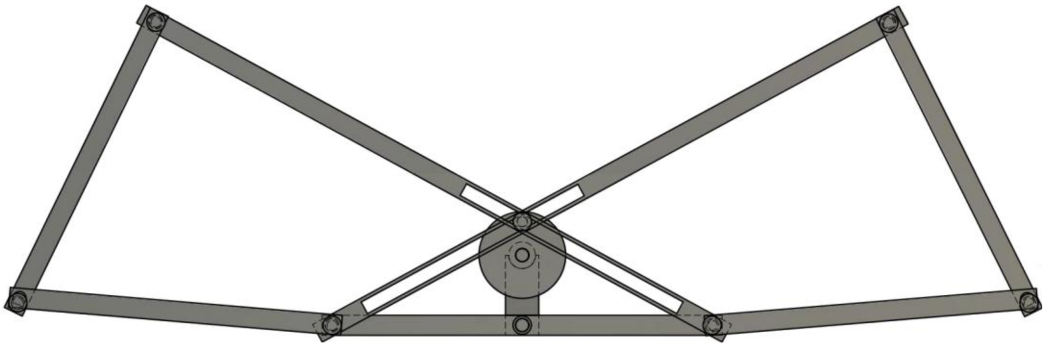
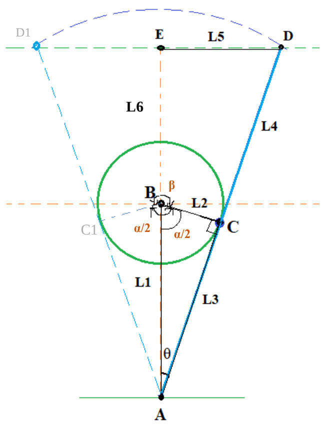


Fig. 1. CAD model of mechanism design for flapping actuation

As illustrated in Figure 2, the rapid return system comprises of novel design coupled toward a disc which spins so at steady velocity. According to the motion of crankshaft, its arm glides across the slots grip, making the slotted-lever to move linearly. The inclination of front motion over the crank is denoted by β, whereas the inclination of reverse motion is denoted by α. As according given in equation, the inclination about forward travel at the crank is proportional to the angle of return motion at the crank (1). Moreover, the processing module period necessary for lever forth some motion exceeds the time necessary for lever returning motion. As the returning movement of the sliding-lever is rapid compared to its front movement, this type of connection can be said to be rapid return technique.



L1 = distance from A to B (fixed)
L2 = distance from B to C (crank radius)
L3 = variable length between A and C (piston sliding the slotted lever)
L4 = variable length between C and D
L5 = variable length between E and D (reciprocating lever and centre line)
L6 = distance from B to E (fixed)
α = angle of return motion from C to C1
β = angle of forward motion from C1 to C
2θ = angle of lever motion from D to D1

Fig. 2. Fast return mechanism

$$\frac{time\ for\ forward\ motion}{time\ for\ return\ motion} = \frac{t_f}{t_r} = \frac{\beta}{\alpha} = \frac{2\pi-\alpha}{\alpha} \quad (1)$$

If the flaps produced at wings are symmetrical without bending or twisting, the average lift across one cycle-period must be nil. however, asymmetric flapping at wings results in a positive average lift. In symmetric flapping, the time spent for downstroke and upstroke is the same. Moreover, in asymmetric flapping, the time required for downstroke (t_{down}) is much greater than the time required for upstroke (t_{up}) [21]. In 2011, Shreyas *et al.,* [22] demonstrated the flow field development of symmetric and asymmetric flapping, indicating t_{down} is less than $t_{up.}$ In contrast, inclination including forward progress at the crank exceeds the inclination of return motion at the crank. As a result, the time needed for lever forward motion is longer than return movement of lever. Hence the Angular velocity for forward motion is different compared to the angular velocity of return motion.

2.1 Crank and Lever Transmission of the Flapping System

As demonstrated in Figure 1, a novel design process is employed to produce a regulated inclination of flapping out of a spinning crank-slider design. It serves the exact required purpose as regular slider-crank device or a rapid backward movement method and is beneficial whenever the necessary sweep of the reciprocating motion is modest relative to the proportions of the operating crank. The Figure 1 consists of a crank and slider mechanism driven by a motor. The sliding levers are connected with two rod linkage forming triangular approach of connection as shown in Figure 3. Hence it is a 4-bar linkage, connection for converting rotary movement to specific angular flapping movement [23]. Like the torque increases, the crankshaft attached to it starts turning towards the identical orientation, forcing the cranked lever to operate adjacent slotting lever throughout the reverse manner. The fixed hinge O, is considered to be origin of the coordinate connected at link1 (l_1), and the link1 is driven by a crank slotter mechanism. θ1 is the instantaneous angle created by slider link1 at origin, θ2 and θ3 are the instantaneous angle created by link2 and link3 in coordination. θ4 is the angle created by the link3 at point C. As illustrated in Figure 3, the range of link1 is limited due to the fact that it is driven by a crank slider mechanism. The movement of link2 and link3 is dependent on the crank-driven movement of link1. Because the linkages self-assemble in the shape of a triangle, we can obtain the required relationships between the crank slider mechanism's links by applying the triangle inequality [24].

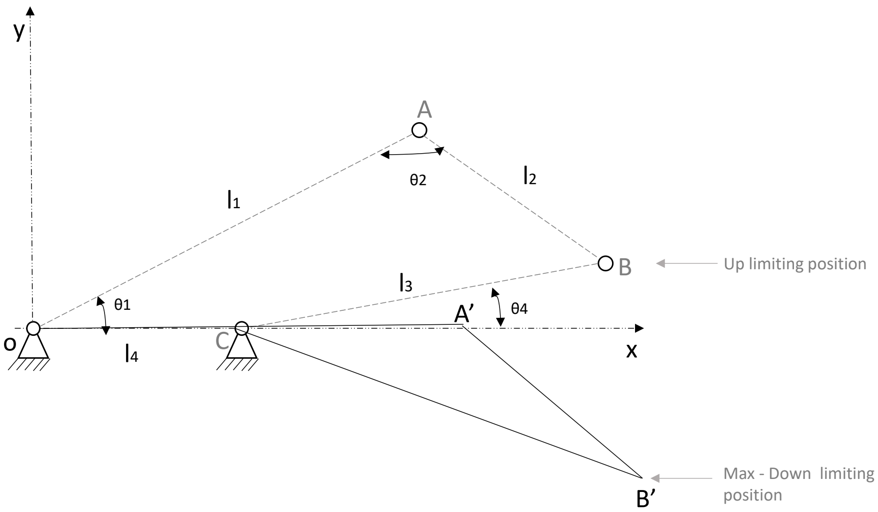


Fig. 3. A limiting positions of the flapping wing mechanism

We obtain,

$$(l_1 - l_4) < (l_2 + l_3) \quad (2)$$

However, from Figure 3,

$$(l_1 + l_2) > (l_3 + l_4) \quad (3)$$

Also, from Eq. (1),

$$\textit{time ratio (Q)} = \frac{time\ of\ nornmal\ stroke}{time\ of\ quick\ retun\ stroke} \geq 1 \quad (4)$$

Equations for the angular displacement obtained from geometry is,

$$[l_1 \cos(\theta 1) + l_2 \cos(\theta 2)] > [l_3 \cos(\theta 3) + l_4 \cos(\theta 4)]$$
$$[l_1 \sin(\theta 1) + l_2 \sin(\theta 2)] > [l_3 \sin(\theta 3) + l_4 \sin(\theta 4)] \quad (5)$$

When the slider position at the crank exceeds 90 degrees, link1 reaches its maximum position, dragging link3 via link2 along with it. When the slider position at the crank exceeds 270 degrees, link1 reaches its minimum position, dragging link3 via link2 along with it. The up and down limiting positions are as shown in the Figure 3. Minimum transmission angle, can be obtained from triangular relationship during maximum down limiting position [25].

For example,

$$\rho = \arccos[((l_2)^2 + (l_3)^2 - (l_1 - l_4)^2)/2.l_2.l_3] \quad (6)$$

The perforated mechanism travels in the both directions linearly with a rotational pitch motion, producing a 25°-35° range of movement. In Flapping Wing Micro Aerial Vehicle (FWMAV) applications, the lever's fluttering action could also be leveraged to create movement by mounting winged design to the slot connection. One complete round of the crankshaft enables the notched fulcrum to generate two flaps. By modifying the dimensions of links AB, BC, and AD as shown in Figure 2, we can easily modify the stroke angles and flapping asymmetry (the lag effect between both the two wings during its flapping motion). Figure 4 depicts the simulations of the lever motion analysis. The structural analysis of the fast return mechanism for the flapping wing was done using commercially available modelling software. The analysis is involving four main steps to solve any modelled problem. In the preliminary step, the creating of the geometry, mentioned the type of analysis and elemental parameters. The pre-processing steps were carried out by adding the material properties and boundary conditions. The solution steps have mesh plot and form of restraints and loads. The final stage has the postprocessing, which involve deformation, mode shapes and stress distribution are to be computed. In the present study, the flapping wing structure of the model is developed and evaluated its stresses and deformation under static loading conditions.

3. Results and Discussions

3.1 Simulation Results of the Flapping Mechanism

In this paragraph, the author describes the functioning of the flap process and equipment with needed couplings and its biomechanical modelling using the GIM® software, that is a recognized program of the Mechanical Engineering Department at UPV/EHU [25]. A kinematic illustration is a geometric representation of a framework wherein suitable joints with elements were being modelled as flawlessly rigid bodies. Figure 4 depicts the layout process with a cranked and two slotting mechanisms coupled in an X-fashion as modelled in GIM® software, along with the resulting work area. The differences in underneath or above concentrations of both flap-acceleration and flap-velocity during both lever motions are displayed by varying colour within every occurrence. The disproportionate movement of the slider is visible from the coloured display of generated point velocity in Figure 4. To demonstrate, a model of a slider-crank mechanism has been created as shown in Figure 3, and the trajectories of points of interest can be visualized. Also, the mechanism's geometry has already been defined and its motion simulated in GIM software. Both actions are accomplished through the use of the Geometry and Kinematics modules.

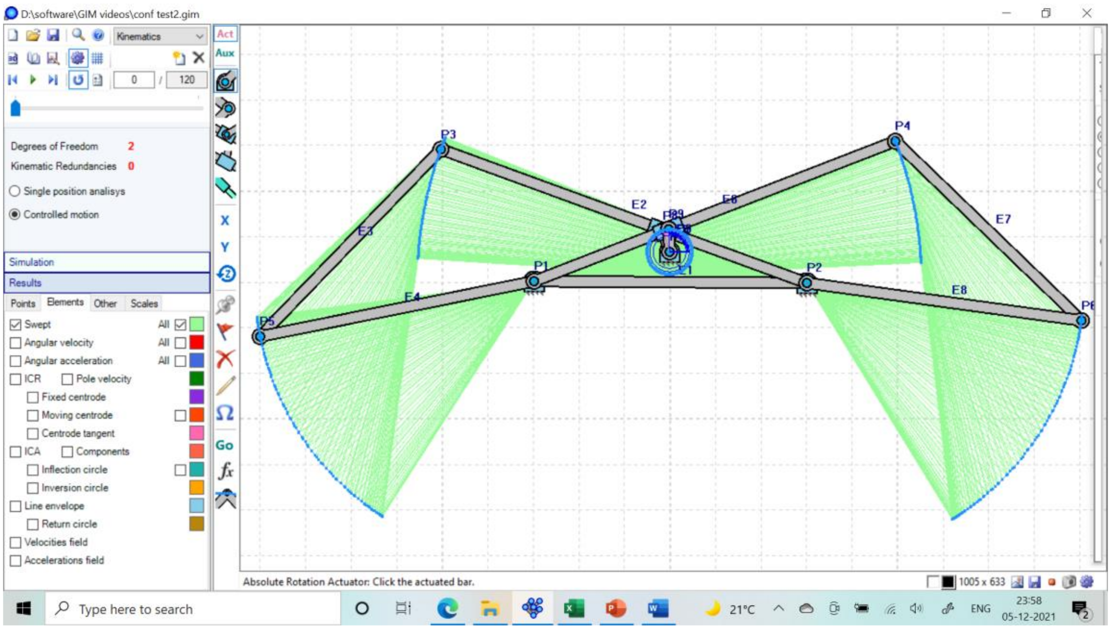


Fig. 4. Workspace of the modelled design mechanism

While both the wings have almost the similar angle of flaps (i.e., 20-25 degrees) at elements E6/E2 and (30-35 degrees) at elements E8/E5 as shown in Figure 4. there is an unavoidable movement coordination lag of 1.5-8 degrees in both designs that may be because of the crank and slotted lever transmission's operation principles. The delay seen at both levers while flapping action along with the Cross synchronization between the levers is caused by the offset nature of proposed design arrangement.

Relative speeds of both the side levers edge/tip locations are with delayed motion compared to one another, that's why there is a lag or velocity distinction between the two lever motion. To acquire the simulation results, a multi-body technique derived from the basic coordinates is used. the motion of the design mechanism is simulated with all nodal trajectories, velocities, and accelerations at required points or position velocity as shown in Figure 5.

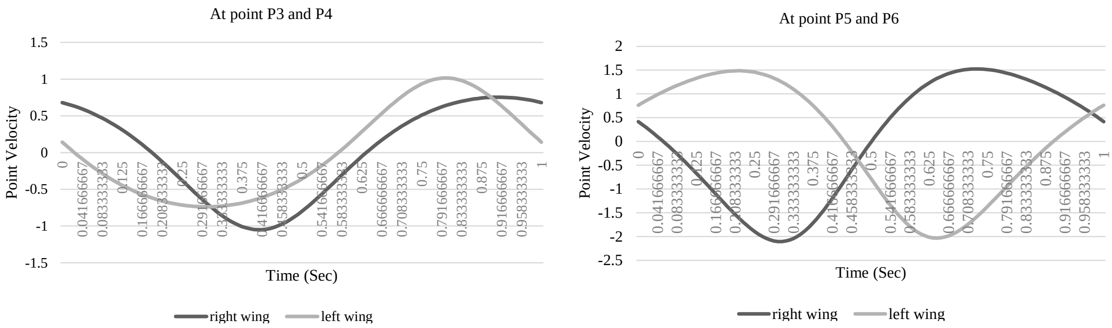


Fig. 5. Point velocity analysis of the design mechanism

However, using GIM software, we were able to obtain simulated results about the kinematic analysis of the design model for the elements E2/E6 and E3/E7 [26]. Figure 7 and Figure 8 show the angle between two vectors at the design mechanism's left and right linkage connections. At the left lever, element E3 forms a maximum angle of 136.66 degrees and a minimum angle of 107.7 degrees at point P3 about the angle formed by two vectors at the design mechanisms with the chosen points P2, P3, P4, and P1 as in Figure 6. At the right lever, element E7 forms a maximum angle of 136.46 degrees and a minimum angle of 107.11 degrees at point P5 relative to the angle formed by two vectors at the design mechanisms' chosen points P1, P5, P6, and P2 as in Figure 7. The Figure 8 depicts the Instantaneous Centre of Acceleration (ICA) of element E7 in relation to the entire design model [27]. Variations in Instantaneous Canter of Acceleration along the paths of element E7 movements are illustrated, with color-coding's indicating under and over-speed of motion representations

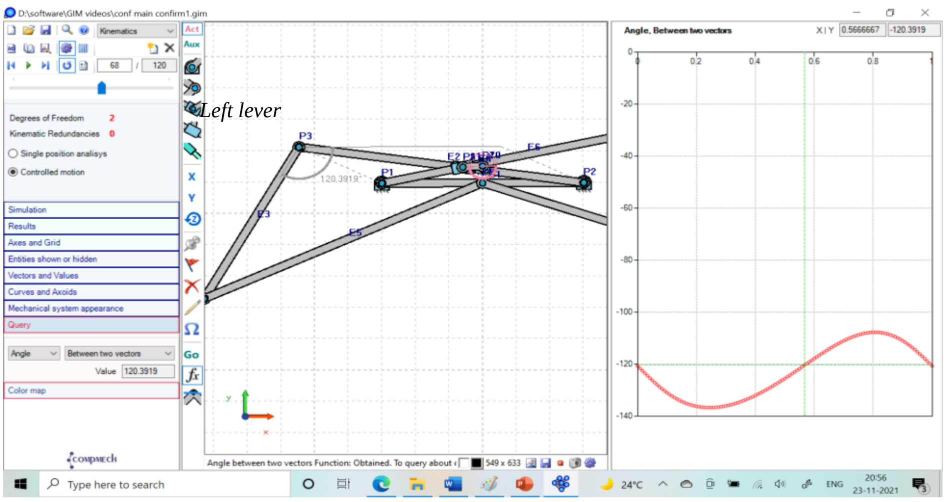


Fig. 6. Angle between two vectors at left lever of the design mechanism

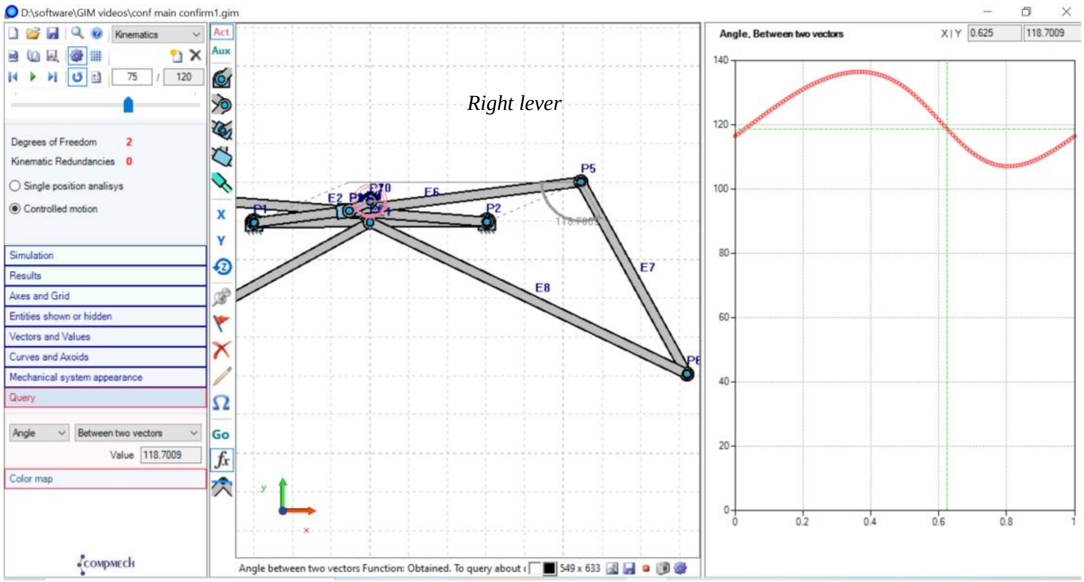


Fig. 7. Angle between two vectors at right lever of the design mechanism

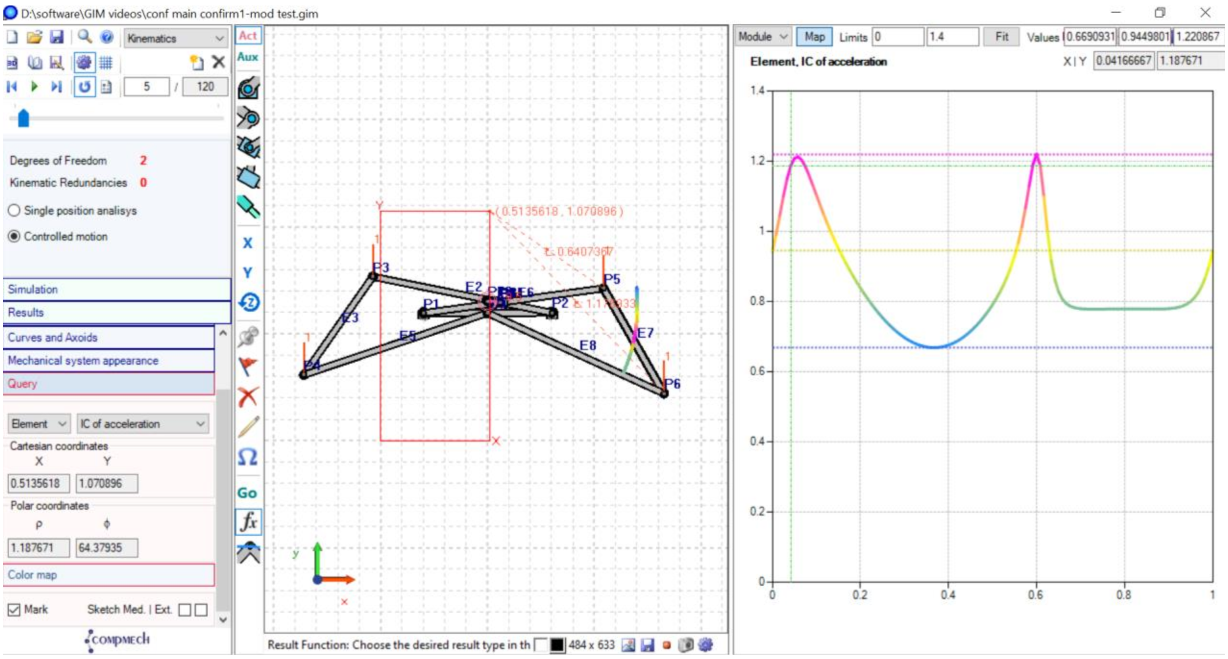


Fig. 8. Element IC of acceleration vs time (sec)

Although the above-mentioned design mechanism is capable of generating flaps near sliding joint connections, its measured point and element velocity and acceleration are highly variable. This seems to be because of constructability restrictions, in that the time required for both levers to swing is not equal, but varied with some lag. Consequently, the aforementioned mechanism design is asymmetric, as it is unable to perform both wings flapping simultaneously with same angle.

3.2 Computational Fluid Dynamic Analysis of the Flapping Wing through CFD

To computationally validate the kinematic results, 2D cross-sectional simplified geometry was used to determine the current suggested design. This simplification is appropriate since the extended arm starts a quick return "stiff body" motion that lacks pivots to consider the effects of flexibility on wing spar. A system to change the volume mesh at each interval must be created in order to represent the stream across the adjustable wing. The current work will confirm the MAV design without limiting the nuances and increased degree of freedom calculations by conducting a non-deforming, spatially dynamic, transient 2D evaluation of flapping wing cross section. The current design uses an articulated pitching mechanism to enable the pitching of rigid wings. The flappable movement is initiated via leading-edge-spars, having a 0.02094395 radians washout angle is considered for the root with tip chords. In order to more accurately reflect the Djojodihardjo [28], Roget *et al.,* [29] and Sitaraman *et al.,* [30] indicated effective thrust-propulsion distribution, 6.875 degree dihedral-angle is provided for the complete flapping-wing arrangement. In addition, a 2D geometry projection of the wing in the XY plane as a flat plate was considered with 3.7 cm in its hight and width of 0.5 cm. Since this design concentrates on the wing-dynamics, the tail is not considered for CFD simulation and just the wings are taken into account [31]. In order to accurately represent the top and bottom models, which play a crucial part in the modelling of the computational domain, boundary conditions must be carefully taken into account. The top and bottom walls must be sufficiently modelled, say 12H–15H, to avoid the flow rebounding effects. The top and bottom limits are simulated as symmetric zones with a 7H clearance from the flat plate zone, respectively, despite the fact that doing so significantly lengthens computation time. Finally, a circle with a diameter of 42 mm and C grid type bodies with arbitrary dimensions were made to use it as a body of influence in order to take into account the dynamical mobility of such plating inside the grids as well as the localized refinement of the trailing-edge region. A graphical illustration of the computational domain is in Figure 9.

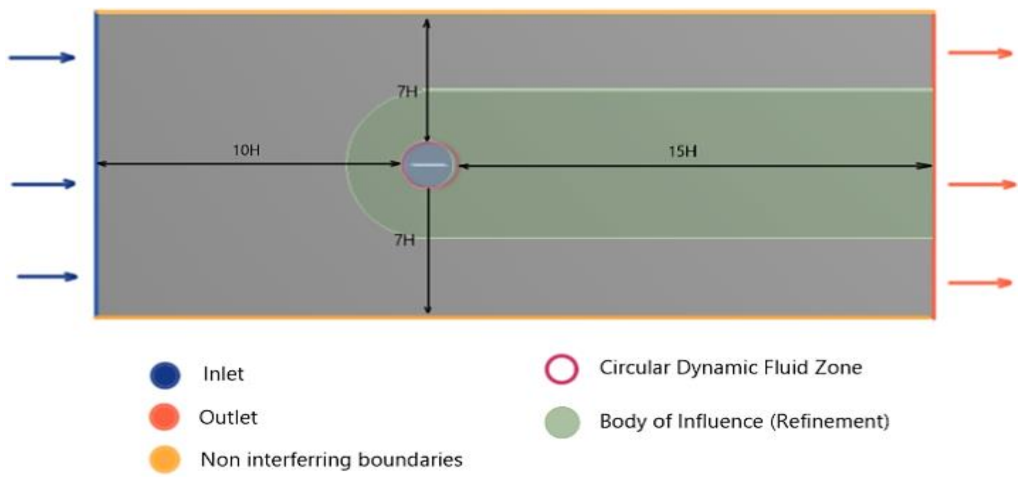


Fig. 9. Discretized domain dimensions

The domain was discretized using solver-specific grid generation techniques, and the incompressible Reynolds averaged Navier-Stokes equation was employed to solve the problem (RANS). RANS equations were essentially created by averaging the N.S. Equations across time. A 20-layer inflation layer with a growth rate of 1.247 was built over the surface of the flat plate in compliance with the mathematical requirement for the inflation reference length.

CFD solver methods can be implemented for the mathematical adjustment of nodes or grids. UDF scripting was used to simulate the circular area surrounding the planar plate of the flappable body. The script was compiled and run utilizing the CFD built-in with C++ codes interpreter to create flappable movements for the round regions. While high angles-of-attack (AOA) limitations for the flappable design, the dynamics of skewing's-nature of the mesh compromises the mesh orthogonal quality and overall mesh quality.

The low speed of operation was considered to calculate the turbulences during the inviscid of flow-domain using a pressure-oriented solvers having iterative 2 equation k-omega SST RANS turbulence-computation and correction for low Reynolds number. The air had an incoming wind of 3.5 m/s operating in the +x direction under normal atmospheric circumstances. Dynamic frame and mesh motion, which were simulated with UDF for each of the exterior and interior interfaces, is essential to creating the flutter motion. To comprehend the transient effects and determine the net thrust generated along the axial direction, the simulation was run for 43,500 iterations, with time steps of 0.001 seconds to get the total simulation result for 1 second. The inviscid fluxes are assessed using a Roe upwind-biased flux-difference method. For time-accurate simulations, a 2^{nd} order COUPLED-scheme is employed, and Newtons-type sub-iteration methods are used to resolve factorizing errors for restoring 2nd order accuracies. For spatial-discretization, a linear way-oriented path of Least Square Cell Based method was utilized, along with a third order MUSCL approach for additional flow and turbulent parameters and a second order iterative pressure calculation [32].

From the computational studies for the proposed design, it is noticed that with higher frequency of flap, there is a severe compromise in the resultant lift and drag coefficients. In previous study performed by Singh *et al.,* [33], for similar geometric modifications, it was inferred that an unsymmetric parabolic trend is noticed in the variation of the flapping frequency for a particular geometric configuration, where increasing the flapping frequency only increased the crucial fluid dynamic properties only to a certain extent. Any modifications further resulted in gradual drop of the performance.

It was noticed that the peak coefficient of lift (attained at approximately 0.05 seconds – periodically) is just about 0.08, which is 72% - 84% lower than the peak lift coefficients obtained in previous explorations made by Singh *et al.,* [33] A similar trend is also noticed in the obtained force and coefficient of drag metric, as depicted in Figure 10, Figure 11, Figure 12 and Figure 13.

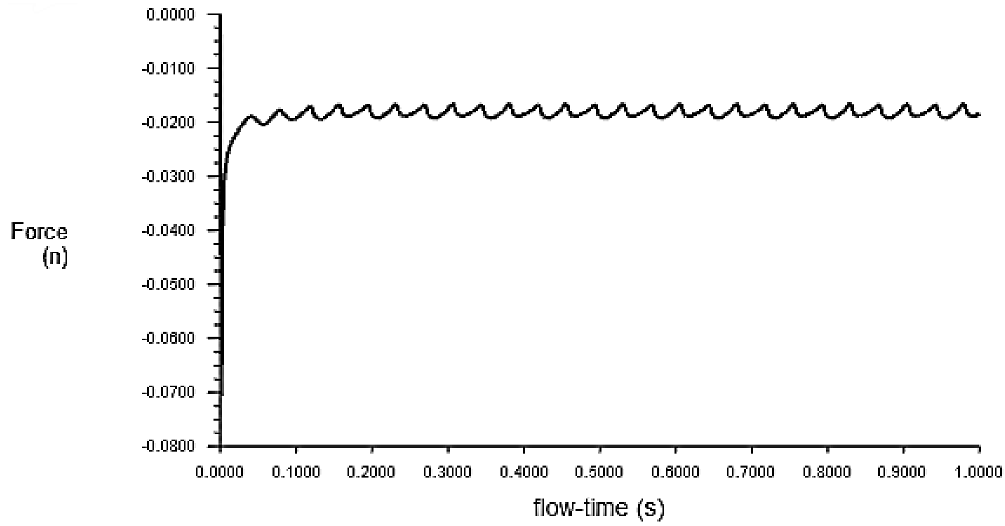


Fig. 10. Transient thrust force plot

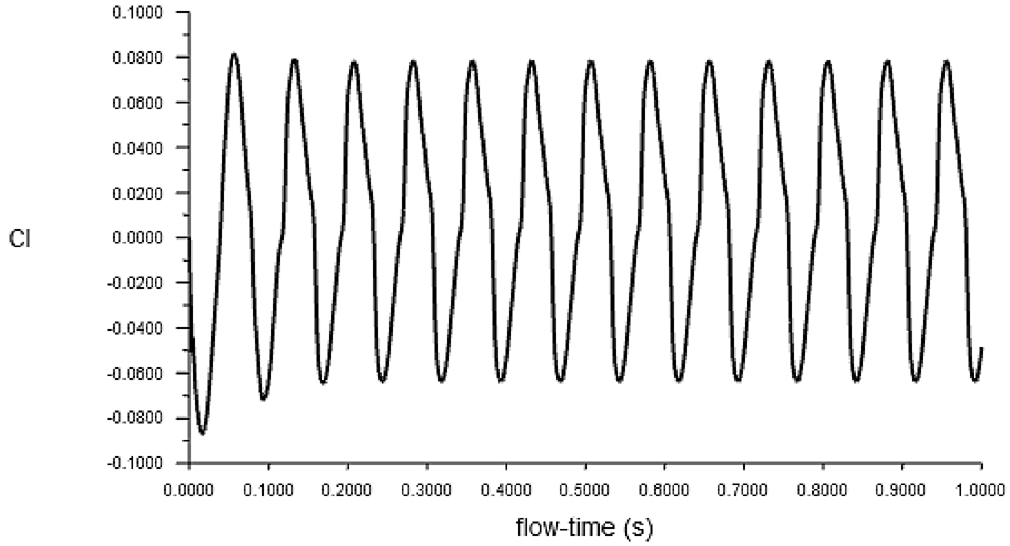


Fig. 11. Transient coefficient of lift plot

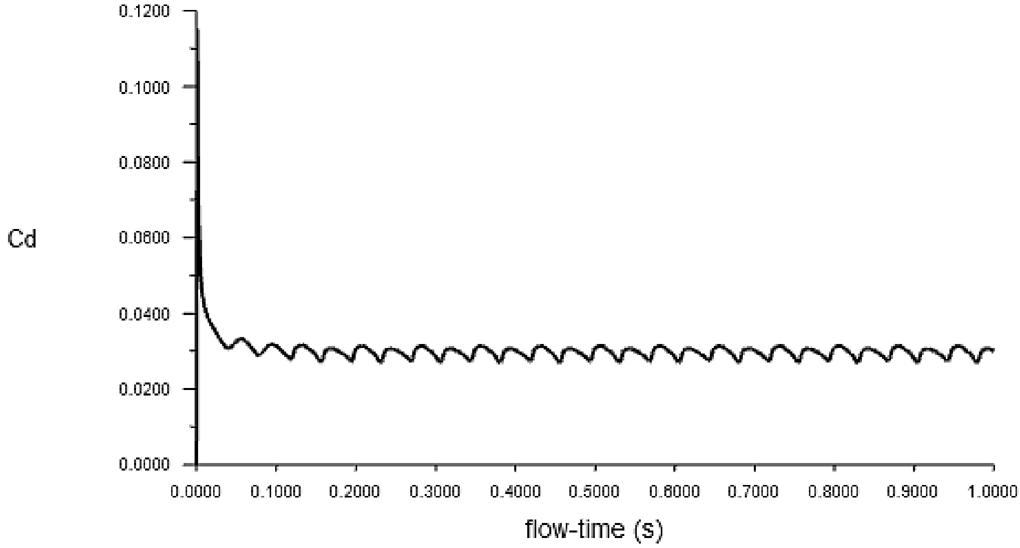


Fig. 12. Transient coefficient of drag plot

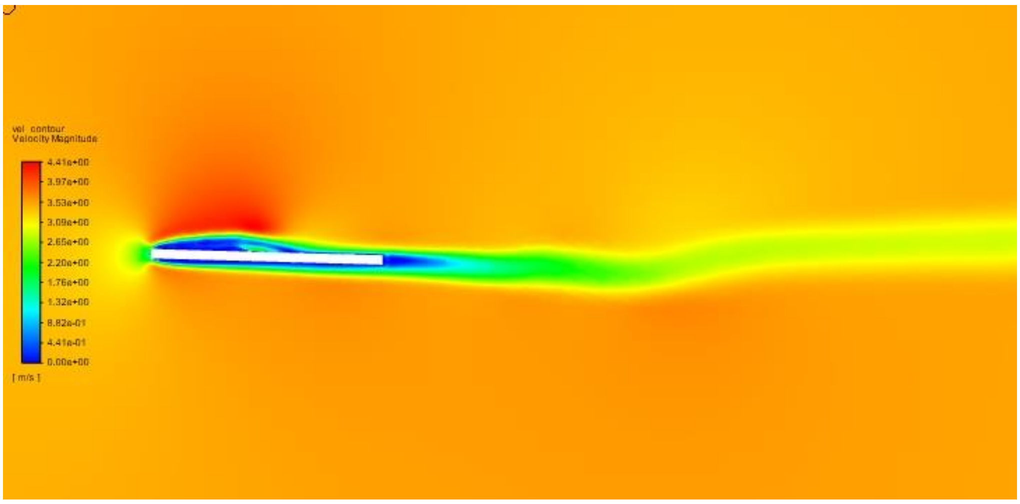


Fig. 13. Downstroke flapping-wing plate with velocity-magnitude contours at the 150 / 314-time frames

4. Conclusions

The paper presents a four-bar flapping wing actuation mechanism model, along with its design analysis and kinematic evaluation. The purpose of this work was to develop a novel mechanism capable of producing a simple and minimal linkage flapping structure. The inspiration for this model comes from the flying method of insects, where it usually employs asymmetric flapping to accomplish lateral dynamic controllability. Here, the fast return mechanism arranged in x pattern converts rotational movement into the required degree of angular flapping movement at varying speeds during one of its up and down strokes. The return stroke is faster than the forward stroke, and also, we have analysed the asymmetric movement variations in both wings using simulations as well as a kinematic analysis of the design mechanisms. Angle between two vectors and Instantaneous Centre of Acceleration for the design model is analysed. Additionally, computational fluid dynamic analysis is performed for understanding the critical aerodynamic parameters in transient conditions. However, the work presented in this paper is limited to verifying the mechanism's performance and does not address the mechanism's dynamic behaviour or resulting characteristics of wing modulation by implementing on flapping wing MAVs. Among several parameters involved in the aerodynamic design of a micro aerial flapping vehicle, there are only a handful of metrics, namely the geometric configuration, flapping frequency and the offset angle playing a critical role in the design. Among these 3 critical parameters, it was parametrically studied that the modification in the geometric configuration and offset angle has lesser influence over the changes made in the flapping frequency parameter.

Conflict of Interest
The authors declare no conflict of interest.

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References
[1] Pornsin-Sirirak, T. Nick, Yu-Chong Tai, Chih-Ming Ho, and Matt Keennon. "Microbat: A palm-sized electrically powered ornithopter." In *Proceedings of NASA/JPL Workshop on Biomorphic Robotics*, vol. 14, p. 17. 2001.

[2] Yang, Lung-Jieh, Cheng-Kuei Hsu, Jen-Yang Ho, and Chao-Kang Feng. "Flapping wings with PVDF sensors to modify the aerodynamic forces of a micro aerial vehicle." *Sensors and Actuators A: Physical* 139, no. 1-2 (2007): 95-103. https://doi.org/10.1016/j.sna.2007.03.026

[3] Conn, A. T., S. C. Burgess, and C. S. Ling. "Design of a parallel crank-rocker flapping mechanism for insect-inspired micro air vehicles." *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* 221, no. 10 (2007): 1211-1222. https://doi.org/10.1243/09544062JMES517

[4] Yang, Lung Jieh, Chung Yu Kao, and Chin Kwang Huang. "Development of flapping ornithopters by precision injection molding." In *Applied Mechanics and Materials*, vol. 163, pp. 125-132. Trans Tech Publications Ltd, 2012. https://doi.org/10.4028/www.scientific.net/AMM.163.125

[5] Hsiao, Fu-Yuen, Lung-Jieh Yang, Sen-Huang Lin, Cheng-Lin Chen, and Jeng-Fu Shen. "Autopilots for ultra lightweight robotic birds: Automatic altitude control and system integration of a sub-10 g weight flapping-wing micro air vehicle." *IEEE Control Systems Magazine* 32, no. 5 (2012): 35-48. https://doi.org/10.1109/MCS.2012.2205475

[6] Yang, Lung-Jieh, Cheng-Kuei Hsu, Hsieh-Cheng Han, and Jr-Ming Miao. "Light flapping micro aerial vehicle using electrical-discharge wire-cutting technique." *Journal of Aircraft* 46, no. 6 (2009): 1866-1874. https://doi.org/10.2514/1.38862

[7] Hubisz, John L. "MicroReviews by the Book Review Editor: Nature's Flyers: Birds, Insects, and the Biomechanics of Flight: David E. Alexander." *The Physics Teacher* 49, no. 4 (2011): 255-255. https://doi.org/10.1119/1.3566056
[8] Alexander, David E. *Nature's flyers: birds, insects, and the biomechanics of flight*. JHU Press, 2002.
[9] De Wagter, Christophe, Matej Karásek, and Guido de Croon. "Quad-thopter: tailless flapping wing robot with 4 pairs of wings." In *9th International Micro Air Vehicles Conference and Competition*, Toulouse, France, pp. 249-256. 2017.
[10] Hines, Lindsey, Domenico Campolo, and Metin Sitti. "Liftoff of a motor-driven, flapping-wing microaerial vehicle capable of resonance." *IEEE Transactions on Robotics* 30, no. 1 (2013): 220-232. https://doi.org/10.1109/TRO.2013.2280057
[11] Hassanalian, Mostafa, and Abdessattar Abdelkefi. "Towards improved hybrid actuation mechanisms for flapping wing micro air vehicles: analytical and experimental investigations." *Drones* 3, no. 3 (2019): 73. https://doi.org/10.3390/drones3030073
[12] Hassanalian, Mostafa, and Abdessattar Abdelkefi. "Effective design of flapping wing actuation mechanisms: theory and experiments." In *54th AIAA Aerospace Sciences Meeting*, p. 1745. 2016. https://doi.org/10.2514/6.2016-1745
[13] Phan, Hoang Vu, Steven Aurecianus, Thi Kim Loan Au, Taesam Kang, and Hoon Cheol Park. "Towards the long-endurance flight of an insect-inspired, tailless, two-winged, flapping-wing flying robot." *IEEE Robotics and Automation Letters* 5, no. 4 (2020): 5059-5066. https://doi.org/10.1109/LRA.2020.3005127
[14] Bejgerowski, Wojciech, John W. Gerdes, Satyandra K. Gupta, Hugh A. Bruck, and Stephen Wilkerson. "Design and fabrication of a multi-material compliant flapping wing drive mechanism for miniature air vehicles." In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, vol. 44106, pp. 69-80. 2010. https://doi.org/10.1115/DETC2010-28519
[15] Bejgerowski, Wojciech, John W. Gerdes, Satyandra K. Gupta, and Hugh A. Bruck. "Design and fabrication of miniature compliant hinges for multi-material compliant mechanisms." *The International Journal of Advanced Manufacturing Technology* 57, no. 5-8 (2011): 437-452. https://doi.org/10.1007/s00170-011-3301-y
[16] Mueller, D., H. A. Bruck, and S. K. Gupta. "Measurement of thrust and lift forces associated with drag of compliant flapping wing for micro air vehicles using a new test stand design." *Experimental Mechanics* 50 (2010): 725-735. https://doi.org/10.1007/s11340-009-9270-5
[17] Singh, Spoorthi, Mohammad Zuber, Mohd Nizar Hamidon, Norkhairunnisa Mazlan, Adi Azriff Basri, and Kamarul Arifin Ahmad. "Classification of actuation mechanism designs with structural block diagrams for flapping-wing drones: A comprehensive review." *Progress in Aerospace Sciences* 132 (2022): 100833. https://doi.org/10.1016/j.paerosci.2022.100833
[18] Keennon, Matthew, Karl Klingebiel, and Henry Won. "Development of the nano hummingbird: A tailless flapping wing micro air vehicle." In *50th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace*
[19] Sukarman, Firdaus, Mohd Ghazali Mohd Hamami, Mazleenda Mazni, Muhammad Amir Mat Shah, and Ahmad Faidzal Khodori. "Parallelogram linkage leg structure for stabilized walking gaits in humanoid robot." *Journal of Advanced Research in Applied Sciences and Engineering Technology* 9, no. 1 (2017): 22-31.
[20] Park, Joon-Hyuk, Emily P. Yang, Chengkun Zhang, and Sunil K. Agrawal. "Kinematic design of an asymmetric in-phase flapping mechanism for MAVs." In *2012 IEEE International Conference on Robotics and Automation*, pp. 5099-5104. IEEE, 2012. https://doi.org/10.1109/ICRA.2012.6225028
[21] Yu, Yongliang, and Binggang Tong. "A flow control mechanism in wing flapping with stroke asymmetry during insect forward flight." *Acta Mechanica Sinica* 21, no. 3 (2005): 218-227. https://doi.org/10.1007/s10409-005-0032-z
[22] Shreyas, J. V., S. Devranjan, and K. R. Sreenivas. "Aerodynamics of bird and insect flight." *Journal of the Indian Institute of Science* 91, no. 3 (2011): 315-328.
[23] Wikipedia. "Four-bar linkage." *Wikipedia The Free Encyclopedia*. Accessed December 4, 2021. https://en.wikipedia.org/wiki/Four-bar_linkage.
[24] Natesan, Arun K. "Kinematic analysis and synthesis of four-bar mechanisms for straight line coupler curves." *PhD diss., Rochester Institute of Technology* (1994).
[25] Jiang, Hongli, Chaoying Zhou, and Peng Xie. "Design and kinematic analysis of seagull inspired flapping wing robot." In *2016 IEEE International Conference on Information and Automation (ICIA)*, pp. 1382-1386. IEEE, 2016. https://doi.org/10.1109/ICInfA.2016.7832035
[26] Macho, Erik, Mónica Urízar, Víctor Petuya, and Alfonso Hernández. "Improving Skills in Mechanism and Machine Science Using GIM Software." *Applied Sciences* 11, no. 17 (2021): 7850. https://doi.org/10.3390/app11177850
[27] Viaña, Javier, and V. Petuya. "A proposal for a formula of absolute pole velocities between relative poles." *Mechanism and Machine Theory* 114 (2017): 74-84. https://doi.org/10.1016/j.mechmachtheory.2017.03.016
[28] Djojodihardjo, Harijono H. "Analysis and computational study of the aerodynamics, aeroelasticity and flight dynamics of flapping wing ornithopter using linear approximation." In *54th AIAA Aerospace Sciences Meeting*, p. 2027. 2016. https://doi.org/10.2514/6.2016-2027

[29] Roget, Beatrice, Jayanarayanan Sitaraman, Robyn Harmon, Jared Grauer, James Hubbard, and Sean Humbert. "Computational study of flexible wing ornithopter flight." *Journal of Aircraft* 46, no. 6 (2009): 2016-2031. https://doi.org/10.2514/1.43187

[30] Sitaraman, Jayanarayanan, Beatrice Roget, Robyn Harmon, Jared Grauer, Joseph Conroy, James Hubbard, and Sean Humbert. "A Computational Study of Flexible Wing Ornithopter Flight." In *26th AIAA Applied Aerodynamics Conference*, p. 6397. 2008. https://doi.org/10.2514/6.2008-6397

[31] Naufal, Muhammad Daffa, Mohd Fairus Mohd Yasin, and Nor Azwadi Che Sidik. "Modelling of Nanomaterial Growth with Flame Enhancement." *Journal of Advanced Research in Applied Mechanics* 90, no. 1 (2022): 1-6. https://doi.org/10.37934/aram.90.1.16

[32] Yusoff, Hamid, Aliff Farhan Mohd Yamin, Siti Nur Amalina Mohd Halidi, Nor Suhada Abdullah, Halim Ghafar, Shafiq Suhaimi, Koay Mei Hyie, and Wan Mazlina Wan Mohamed. "The Optimisation of Aerodynamic Performance Enhancement of a Flapping Wing using Response Surface Methodology." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 91, no. 1 (2022): 69-82. https://doi.org/10.37934/arfmts.91.1.6982

[33] Singh, Spoorthi, Aravind Karthik Muralidharan, Jayakrishnan Radhakrishnan, Mohammad Zuber, Adi Azriff Basri, Norkhairunnisa Mazlan, Mohd Nizar Hamidon, and Kamarul Arifin Ahmad. "Parametric Study and Experimental Investigations of a Single Crank-Slotted Dual Lever Mechanism for MAV Flapping Actuation." *Biomimetics* 7, no. 4 (2022): 208. https://doi.org/10.3390/biomimetics7040208