Conceptual Design of a Low - Cost Linear Actuator for Variable Span Wing Application

Aynul HOSSAIN*

*Corresponding author
School of Aerospace Engineering, Shenyang Aerospace University,
37 Daoyi South St, Shenbei, Shenyang, Liaoning, China 110136,
aynul.auvi007@gmail.com

DOI: 10.13111/2066-8201.2021.13.1.7

Received: 16 October 2020/ Accepted: 16 November 2020/ Published: March 2021

International Conference of Aerospace Sciences "AEROSPATIAL 2020", Virtual Conference
15-16 October 2020, Bucharest, Romania,
Section 4 - Materials and Structures

Abstract: *Aerospace actuators can be found throughout modern commercial and experimental aircraft, as well as in military and space exploration. The aerospace industry is not only growing, but also rapidly changing and the demand for aerospace actuators is permanently increasing. Linear actuator is able to push, pull, and hold objects in a way that our bodies cannot. Additionally, electrically powered technology provides more sophisticated control options. Linear actuator drive many different functions that are essential to safe and efficient aircraft operation. Manufacturers and hobbyists alike are always on the hunt for new ways to automate functions while keeping development costs low. Providing cost-effective linear solutions for aerospace application is one of the biggest challenge. This research will provide a cost-effective actuator conceptual design for variable span morphing wing UAV. The cost-effective design will be presented along with the application-based selection of linear actuators for morphing wing UAV.*

Key Words: *Actuation, Linear, Rack, Pinion, Variable span*

1. INTRODUCTION

In this proposed linear actuator, the mechanical rotational motion of a freely rotated servo is converted to linear motion.

By converting electrical energy into mechanical energy, linear actuators allow actuation to be completed swiftly without manual work.

They can push, pull, and hold objects with greater force, speed, and precision which can be operated in inaccessible spaces where hazardous environments exist. For the presented actuator, a pinion is engaged to a servo- gear and rack.

The rack extends or retracts along the actuator guide, which can be fixed to the main wing internal structure or spar.

Such geometry changes are much more substantial than conventional methods and to accommodate large wing planform change while overcoming weight penalties [1] significant advancements in both materials and actuator technology are required.

2. APPLICATION BASED SELECTION OF LINEAR ACTUATOR

In aviation, the actuators manage several steering applications by controlling the ailerons, elevators, trims, and rudder. Manufacturers have also developed special aerospace actuators to open and close an aircraft's cargo doors. Now, companies are beginning to fit aircrafts with electric actuators instead of hydraulic actuators that were used in the past because of better technology and more reliability.

Heavy-duty actuators can withstand high pressure and are built strong to prevent damage. For experimental application, linear actuator can be used in morphing wing technology. But finding a suitable linear actuator for morphing wing is not an easy job. So, implementing a successful linear motion system starts with selecting the appropriate actuator based on application needs. The aerospace manufacturers and designer must account for the necessary characteristics of the linear actuator which including:

Stroke Length – The distance the actuator travels in one direction. Hydraulic actuators' stroke length ranges from mm to meter. Pneumatic actuators provide a stroke length of less than 1 m, and electromechanical actuators work in an unlimited range of stroke lengths, based on the stroke, the shortest and longest dimensions of the actuator.

Mounting Styles – Dual-pivot mounting method allows the actuator to pivot on both sides as it extends or retracts. It allows the application to move on a fixed path while maintaining two free pivot points.

Stationary mounting can be applied by having a shaft mounting bracket securing the actuator to an object along the shaft. It is generally used in applications where the linear actuator is needed to push something head on, such as triggering a button or pushing a bellow to compress or inflate.

But for extendible and retractable actuation, much clearance needed for actuation during retract condition as one of the parts connected to outer movable wing.

Speed – Measured in distance (m) per second, actuator specification determines rated speeds. According to the application, different speeds can be applied using a programming board.

Feedback – Arduino UNO board is a perfect choice for the actuation control. Programming can control the actuator with multiple conditions for mission planning of a variable span morphing wing.

Properties (Actuation forces, Speed) of servo actuated linear actuator can be achieved using the formula listed below:

In the following formulas, the following notations were used: *M* mass to move (Kg); *V* linear speed (m/s); *t* time (s); *a* acceleration (m/s^2); *g* gravity (9.8 m/s^2); *F* external force (N); *d* Pitch diameter of pinion (mm); T_P torque (Nm); N_P maximum rotational speed (RPM).

$$a = \frac{v}{t} \tag{1}$$

$$F_r = \mu M * g + M * a + F \tag{2}$$

$$T_p = \frac{F_r * d}{2000} \tag{3}$$

$$N_p = \frac{V * 19{,}100}{d} \tag{4}$$

$$Gear\ ratio = \frac{number\ of\ teeth\ in\ driven\ gear}{number\ of\ teeth\ in\ driver\ gear} \tag{5}$$

In the following formula, K_A is the coefficient of working condition; K_V, represents the coefficient of dynamic load; K_{Ha} is the transverse load distribution coefficient of the contact strength; K_β represents the distribution coefficient of the tooth lead load; Z_H is the coefficient of node cell; Z_E is the coefficient of elasticity; Z_τ is the coefficient of the overlap ratio.

$$\text{From Hertz formula}, \sigma_H = \sqrt{\frac{F}{\pi L}\frac{\frac{1}{R}}{\frac{1-V_1^2}{E_1}+\frac{1-V_2^2}{E_2}}} \tag{6}$$

The contact stress of gear and rack transmission derived by the Hertz theory can be expressed as following:

$$\sigma_H = Z_H Z_E Z_e \sqrt{\frac{F_1}{bd_1}\frac{u \pm 1}{u}} K_A K_V K_{H\infty} K_\beta \tag{7}$$

3. DESIGN OF LINEAR ACTUATOR

This section is intended to present the conceptual design of a linear actuator that can help to perform in flight span variations, a variable-span wing actuation. The designed linear actuator consists of three main parts, namely the actuator guide, the rack-pinion, and servo. This section will present those three parts that have been designed using CATIA V5.

For the actuation, a freely rotated servo has been considered instead of a motor as servo has less weight and strong actuation force. With the advantages of high transmission efficiency, strong carrying capacity and the stability of the transmission ratio, the gear and rack transmission system is commonly used in force and motion transmission in the mechanical system. The reliability and stability of the gear and rack directly influence the regular operation of the actuator [2, 3].

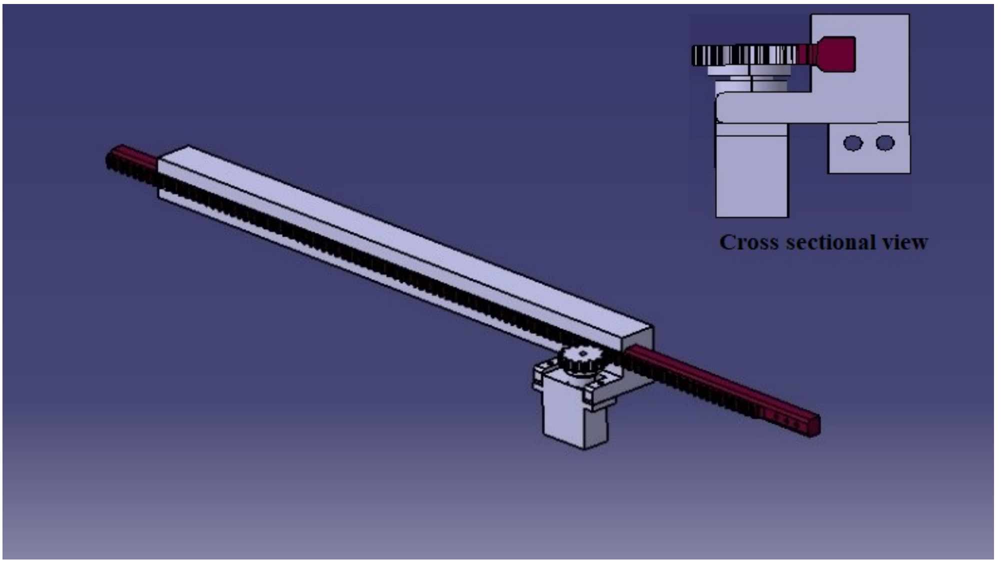

Fig. 1 Assembled linear actuator

Actuator guide: Actuator guide will provide housing and shielding for the rack that can easily extend-retract. An extremely negligible frequency will be transferred through the rack to the actuator guide. This part of linear actuator can easily be connected to the rib or any other internal part of the wing.

Table 1. Design specification

Parameter	Value/Unit
Stroke length	300 mm
Weight	50 g
Actuation time	3 s
Actuation force	2.6 kg

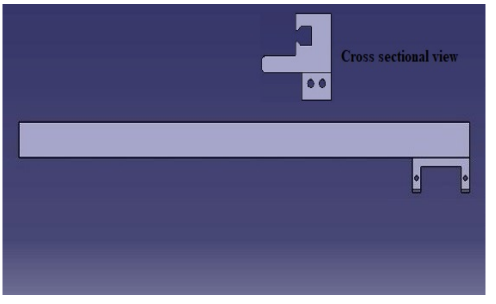

Fig. 2 Actuator guide

Rack and pinion: They are composed of two gears. The pinion is the normal round gear, and the rack is the straight one. The rack can be viewed as a gear, but its radius is infinite. The rack has teeth cut in it and they mesh with the teeth of the pinion gear. The pinion rotates and moves the rack in a straight line and changes the rotary motion to a linear motion. The rack has been designed connected to outer movable wing spar and the pinion will be connected to servo.

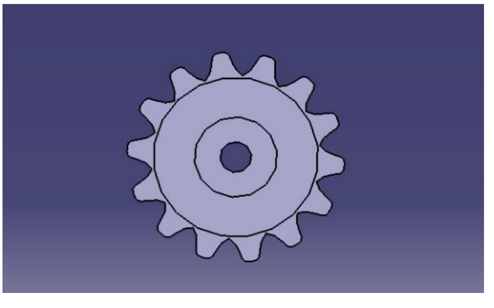

Fig. 3 CATIA V5 designed pinion

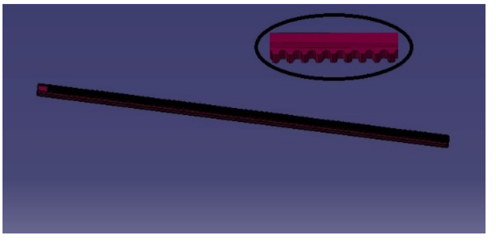

Fig. 4 CATIA V5 designed rack

The inboard spar is translated horizontally by a servo-driven linear actuator located inside the wing. The outer wing spar is then connected to the inboard wing section at the joint which is located inside the wing box. The inboard actuator then connects at the joint to the outboard spar at roughly the quarter-span point. The outboard wing region is activated independently of the inboard region by means of a servo attached between ribs. An illustration of the spar configuration, with corresponding attachment, can be seen in Fig. 5. The linear actuation can be powered by 12V/6V power sources depending on the servo we use. By extending and retracting the rack, linear actuator stroke lengths can vary from ±15 mm to ±300 mm.

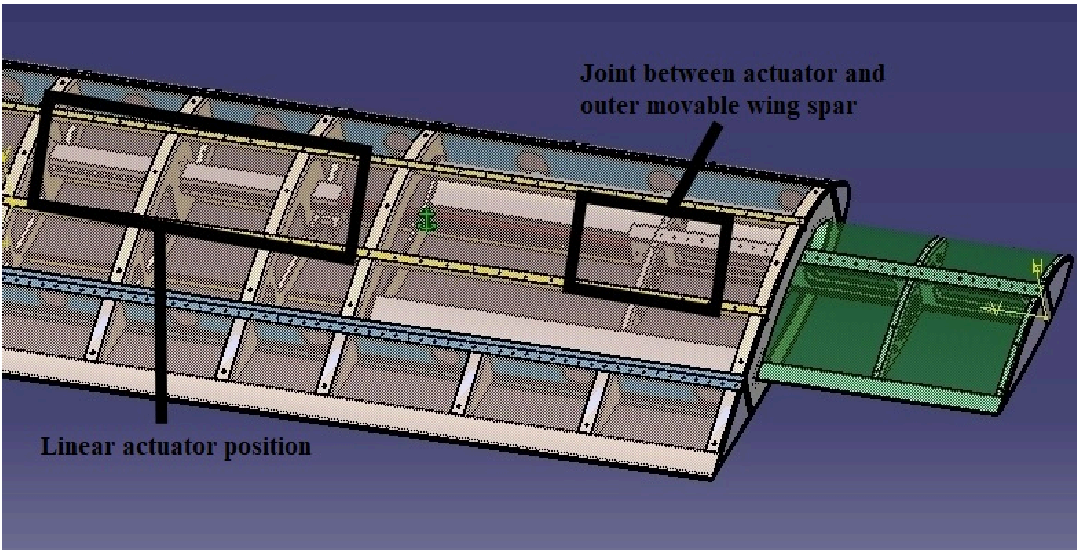

Fig. 5 Linear actuator mounted position between wing ribs

4. APPLICATION OF THE LINEAR ACTUATOR IN MORPHING WING

Linear actuation for variable span morphing wing has been found to be one the reasonable mechanism for many researchers and engineers. The design of adaptive structure mechanisms and actuator, along with the development of smart materials actuator that allow bio-inspired configurations of aircraft is highly desired for the near future and is currently one of the most interesting research areas.

The new concepts and technologies under development are now are a constant attempt to enhance the overall flight performance of aircraft and UAVs.

Improved maneuverability is highly dependent on the linear actuators speed and stroke length.

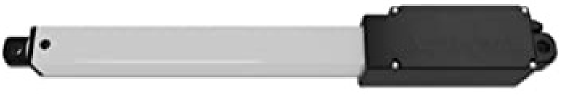

Fig. 6 ACTUONIX P16-P linear actuator

In the past there have been many morphing wing successful projects that have used linear actuators. Bishay PL et al and Burg E et al previously used commercial linear actuator in their span morphing wing core design [4].

The reaction force in the direction of the actuation was found to be 8.05 N, which the linear actuators are more than capable of delivering (L12-R Actuonix Linear Electric Actuator [5] in Fig. 6 can provide 42 N output force).

Variable span morphing wing design using linear actuator has been demonstrated in a research which includes João R.C. et al and Mestrinho et al [6].

They also successfully carried out flight test of variable span wing UAV [7]. Almost half of the main wingspan extension is possible using linear actuator. But it is yet to demonstrate that full wingspan extension is possible using linear actuator. In such case one may meet several structural optimization challenges.

The model presented in the works of Neal et al and David A. et al also uses five linear actuators to control the wing shape [8]. Pneumatic actuators were chosen for the wing and tail extensions because of large strokes, as they are lighter than hydraulic or electromechanical actuators. The University of Florida has investigated the effect of a biologically inspired variable gull-wing morphing UAV.

This kind of small aircraft can change the angle between the inboard and outboard wing sections in flight to vary performance capability. A jointed spar structure controlled by a vertical linear actuator enables gull-wing morphing [9].

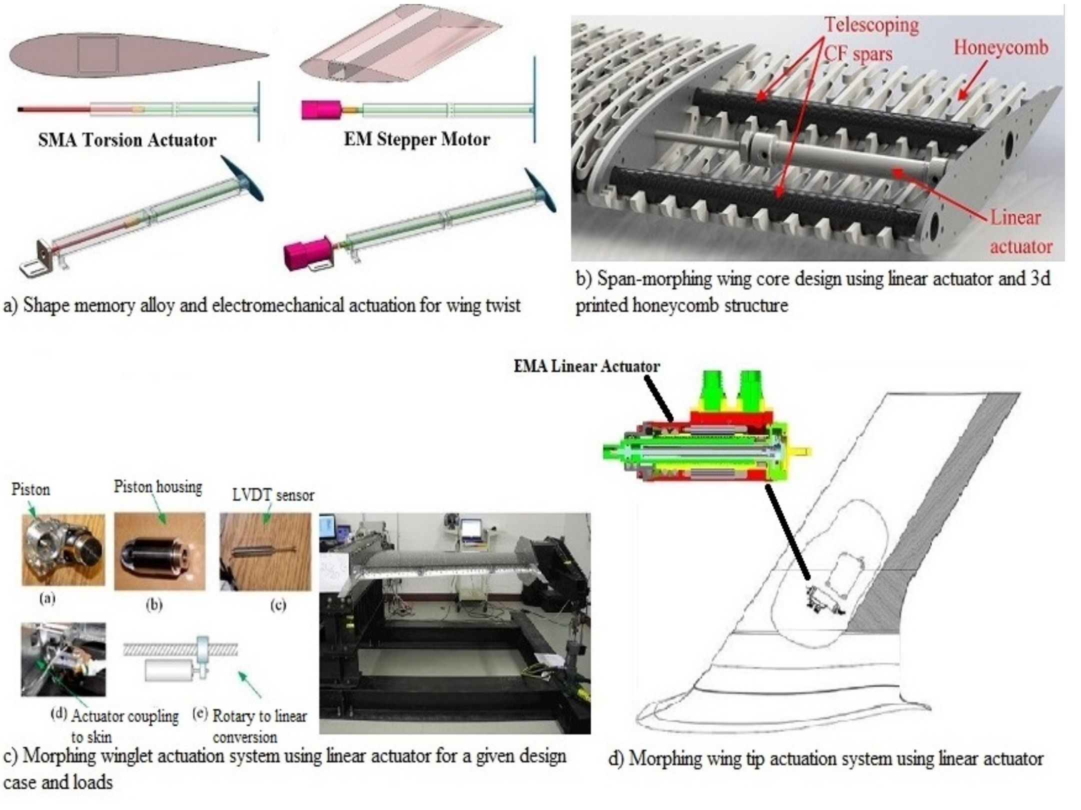

Fig. 7 Different kind of existing actuation method using linear actuator

Also, the SMA behavior has been modelled according to the model proposed by Liang and Rogers, simulation results being presented in terms of output displacements and morphed shape.

The linear actuators incorporated in a statically determined structure around which a prototype airfoil has been built, were used for morphing; finally, the prototype airfoil was tested in the wind tunnel to analyze drag reduction [10].

Others have investigated the methods to actuate morphing wing sections; novel methods such as compliant mechanisms have been studied extensively [11, 12, 13].

Strelec et al used two-way SMA wires as linear actuators attached to certain points inside a shell, whose geometry was an airfoil, made of ABS.

When heated, the SMA wires contracted, cambering the airfoil and, when they had been cooled, the airfoil returned to its previous shape.

Experimental results proved that there was a trailing edge deflection of 6.0 mm. The linear actuator and the mechanical system are also suitable for a morphing winglet [14].

A direct comparison between the shape memory alloy and the electromechanical actuation for wing twist [15] has been previously done by James M. et al and Sam F. et al who discussed

The combination between the linear actuator and the shape memory alloy actuation. In the last few years of the morphing wing research, the linear actuator use has been greatly considered along with the shape memory alloy.

5. CONCLUSIONS

The conceptual design of a low-cost linear actuator was developed by using an actuation mechanism based on some miniature high force in house developed electrical linear actuators. This paper illustrated the conceptual design of the miniature linear actuator used in the actuation mechanism of the variable wingspan concept. Designed and presented as a part of the morphing wing project, the actuator consists of a miniature servo, a gearing system, and a rack guide. Therefore, to obtain the overall model of the actuator, a commercial model of a freely rotated servo was chosen. Further, the model was extended by adding the mechanical components. The model presented in this paper is cost-effective and much more simpler than any other actuation method for variable span morphing wing.

REFERENCES

[1] L. F. Campanile, Initial Thoughts on Weight Penalty Effects in Shape-adaptable Systems, *Journal of Intelligent Material Systems and Structures*, **16**(1): 47-56, Doi:10.1177/1045389X05046692, 2005.

[2] X. Yanjun & H. Lihu & Z. Jiayu & X. Yanchun, Dynamic Analysis of Gear and Rack Transmission System, *The Open Mechanical Engineering Journal*, **8**: 662-667, 2014.

[3] X. Q. Zhang, D. G. He and R. Zheng, Contact Stress Analysis of Gear and Rack, *Journal of Mechanical Transmission*, vol. **7**, pp. 30-32, 2011.

[4] P. L. Bishay, E. Burg, A. Akinwunmi, R. Phan & K. Sepulveda, Development of a New Span-Morphing Wing Core Design, *Designs*, **3**, 12. 10.3390/designs3010012, 2017.

[5] * * * Actuonix Motion Devices Inc (2018), *ACTUONIX P16-P Linear Actuator with Feedback*, Available at https://www.actuonix.com/P16-P-Linear-Actuator-p/p16-p.htm.

[6] J. Mestrinho & P. Gamboa, & P. Santos, *Design Optimization of a Variable-Span Morphing Wing for a Small UAV*, 10.2514/6.2011-2025, 2011.

[7] P. Santos, J. Sousa, P. Gamboa, Variable-span wing development for improved flight performance, *Journal of Intelligent Material Systems and Structures*, **28**(8):961-978, Doi:10.1177/1045389X15595719, 2017.

[8] D. A. Neal, *Design, Control, and Experimental Modelling of a Morphing Aircraft Configuration*, 2005.

[9] M. Abdulrahim & R. Lind, *Flight Testing and Response Characteristics of a Variable Gull-Wing Morphing Aircraft*, 5113. 10.2514/6.2004-5113, 2004.

[10] S. Barbarino, R. Pecora, L. Lecce, A. Concilio and S. Ameduri, *Airfoil Morphing Architecture Based on Shape Memory Alloys*, Proceedings of the ASME 2008 Conference on Smart Materials, Adaptive Structures and

Intelligent Systems, Volume **1**, Ellicott City, Maryland, USA. October 28–30, 2008. pp. 729-737. ASME, https://doi.org/10.1115/SMASIS2008-480.

[11] L. Saggere & S. Kota, Static shape control of smart structures using compliant mechanisms, *AIAA Journal*, 2003, 37(5):572–578.

[12] D. S. Ramrkahyani, G. A. Lesieutre, M. Frecker, & S. Bharti, *Aircraft structural morphing using tendon actuated compliant cellular trusses,* 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, *AIAA Paper-2004-1728,* Palm Springs, California, 19-22 April 2004.

[13] K. Manute & G. W. Reich, *An aeroelastic topology optimization approach for adaptive wing design,* 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, *AIAA Paper 2004-1805*, Palm Springs, California, 19-22 April 2004.

[14] I. Dimino, G. Amendola, B. Di Giampaolo, G. Iannaccone and A. Lerro, *Preliminary design of an actuation system for a morphing winglet, 2017 8th International Conference on Mechanical and Aerospace Engineering (ICMAE),* Prague, 2017, pp. 416-422, doi: 10.1109/ICMAE.2017.8038683.

[15] J. Mabe, S. Frederes, D. Hartl and F. Carpenter, *A direct comparison of shape memory alloy and electromechanical actuation for wing twist applications, Proc. SPIE 11377, Behavior and Mechanics of Multifunctional Materials IX*, 113770L (28 April 2020); https://doi.org/10.1117/12.2557695.