

SIZING OF LINEAR ACTUATORS FOR SPAN EXTENSION OF HALE UAV

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Abstract

In order to effectively predict the penalties of span extension for HALE UAV wings, there is need of a preliminary model for actuator weight and size estimation. Actuator design is an involved process requiring the use of several detailed design parameters such as operating pressure and mounting arrangement, which are outside the scope of the preliminary aircraft design process.
Three kinds of actuators are considered suitable for span extension morphing of HALE UAV wings, viz., Electromechanical, Hydraulic and Pneumatic. Based on what is already available, each of these types corresponds to a range of force and stroke combinations. For lower values of span extension, lighter Pneumatic actuators are suitable. Hydraulic and Pneumatic actuators have an overlap for medium values of span extension. For longer extensions, telescopic Hydraulic actuators are the only available option, though they are found to be significantly heavy. Two different approaches to actuator modelling are proposed, FINDACT and DESACT, using an actuator selection and design approach respectively
The actuator models were then utilised in a framework for estimation of Endurance of a HALE UAV with span-extended wings. It was found that selecting only existing actuators using FINDACT leads to jerky solutions for actuator mass as the model abruptly switched between different classes of actuators. DESACT is a model which interpolates between existing actuators and generates a notional actuator meeting the force and stroke requirements for each telescopic span morphing scenario. On following this approach, it was found that the results became smoother and less heavy. A representation of variation of actuator weight with increasing span and its effect on Endurance is evaluated and presented.

Keywords: actuator selection, telescopic span extension, morphing wing, aircraft design

1. General Introduction

An aircraft is designed for a particular set of requirements, and the design is typically a weigh-off between these requirements. Morphing the aircraft geometry presents the opportunity to extend some of the performance specifications. In the case of telescopic span morphing, Endurance benefit is expected by achieving greater aerodynamic efficiency due to the higher aspect ratio that can be achieved by this method.
Span morphing is when the wingspan is varied in flight. The mechanism itself of span morphing has been a subject of recent work. Several schemes have been proposed, implemented and tested, such as scissor mechanism [1, 2], twist-spar concept [3], rack-and-pinion arrangement [4, 5] or belt-drives [6]. Some early work in span morphing was performed using a telescopic pneumatic spar concept [7], in which wind tunnel tests were performed to demonstrate improvement in lift-to-drag ratio when the span was extended.

1.1 Concept of Telescopic Span Morphing

Suppose a baseline aircraft is to be given a telescopic span extension of a particular amount, as described in Figure 1. The telescoping wingtip (1) is housed inside the main wing in retracted condition. Whenever span extension is desired, a linear actuator (2+3) pushes the wingtip outwards as

shown. Bearings and guides could be provided along the line of sliding contact (4). To save space, a telescopic actuator can be used.

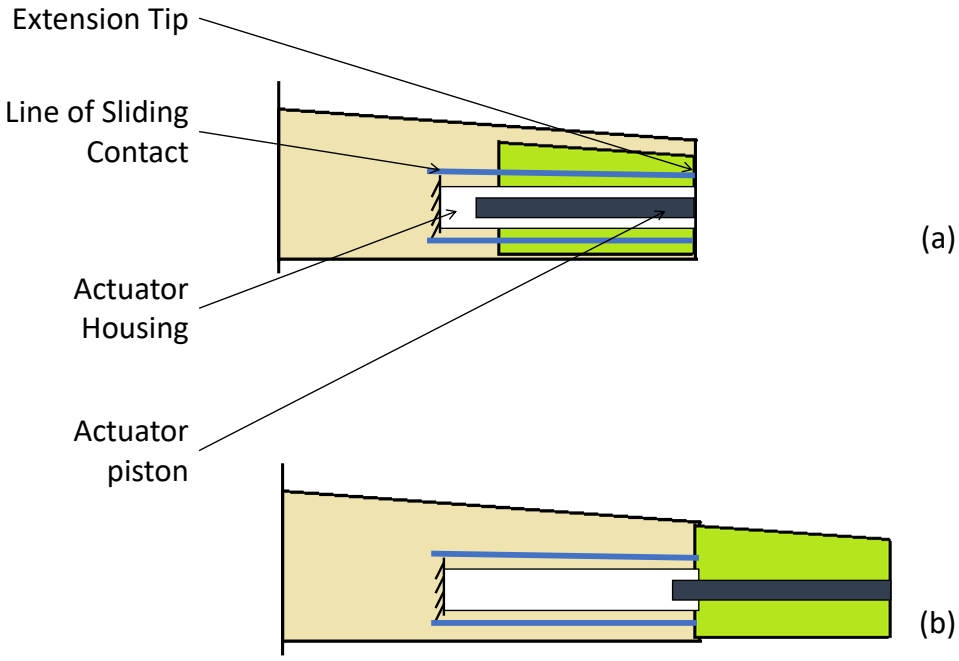


Figure 1 – Conceptual layout of single stage telescopic span morphing mechanism (a) retracted (b) extended

1.2 Actuators for Span Morphing

The type of actuator chosen heavily depends on the type of morphing and the mechanism employed for it. For span morphing in particular, the actuation requirement is characterised by large span and relatively small force requirement [8]. While many span morphing systems rely on readily available Commercial Off The Shelf (COTS) rotary electromechanical actuators, some published work is available on innovative actuators especially designed for the purpose of span morphing such as [9, 10]. However, since such instances are few and not yet demonstrated on full-scale span morphing, a survey and comparison of available COTS actuators is carried out, spanning Pneumatic, Hydraulic and Electromechanical Actuators and a comparison is published in [8].

2. Actuator Selection Algorithm

A need was felt to have an actuator model that can take input of the the stroke and force requirement for telescopic span morphing and provide as output, the weight and space occupied by that actuator. This would help in correctly evaluating the change in aircraft performance due to the increase in weight and in the case of a wet wing, the fuel lost in the space where the actuator is housed. Previous work by the authors proposed actuator design and models based on machine design principles, or linear regression interpolation of various actuator design variables [11, 9]. These models used a maximum of three independent variables like stroke, force and number of stages, to calculate actuator parameters such as weight and size.

However, in reality, design of actuators is an involved process. There are many independent variables, such as operating pressure, material, construction type, which need to be accounted for, but are not directly relevant to this scope of work. To include the effect of these variables, a catalogue-style mathematical model is proposed which can be implemented to select the best actuator using top-level aircraft design variables in the design framework.

For actuator selection, several options are available. The type of linear actuation could be Pneumatic, Hydraulic or Electromechanical. A database was created, consisting of 60 linear actuators from various commercial sources, which broadly meet the load and stroke capacity requirements for a span extension application.

2.1 FINDACT Algorithm

The $FINDACT$ algorithm is developed such that it can take input for the required span extension and load capacity and to select an actuator from the database to best suit the telescopic span morphing requirement.

FINDACT gives two values: actuator weight and actuator space (closed length). The weight is used to update the morphed aircraft empty weight and the space is used to determine the space in the wing that is unusable for wing fuel tanks. This is in turn used to calculate volume of fuel lost, and hence new Endurance.

3. FINDACT Methodology for Actuator Sizing

A model called *GENENG* [12] was available in literature, for prediction of performance of a generic turboprop engine using available data of existing engines. *GENENG* uses an algorithm called ballparking for interpolation between members of the database, an approach which was readily adaptable to the present design problem. The ballparking algorithm was adapted to develop a model called *FINDACT* which is able to find a generic notional actuator using a database of existing actuators. The *FINDACT* algorithm is summarised in Figure 2.

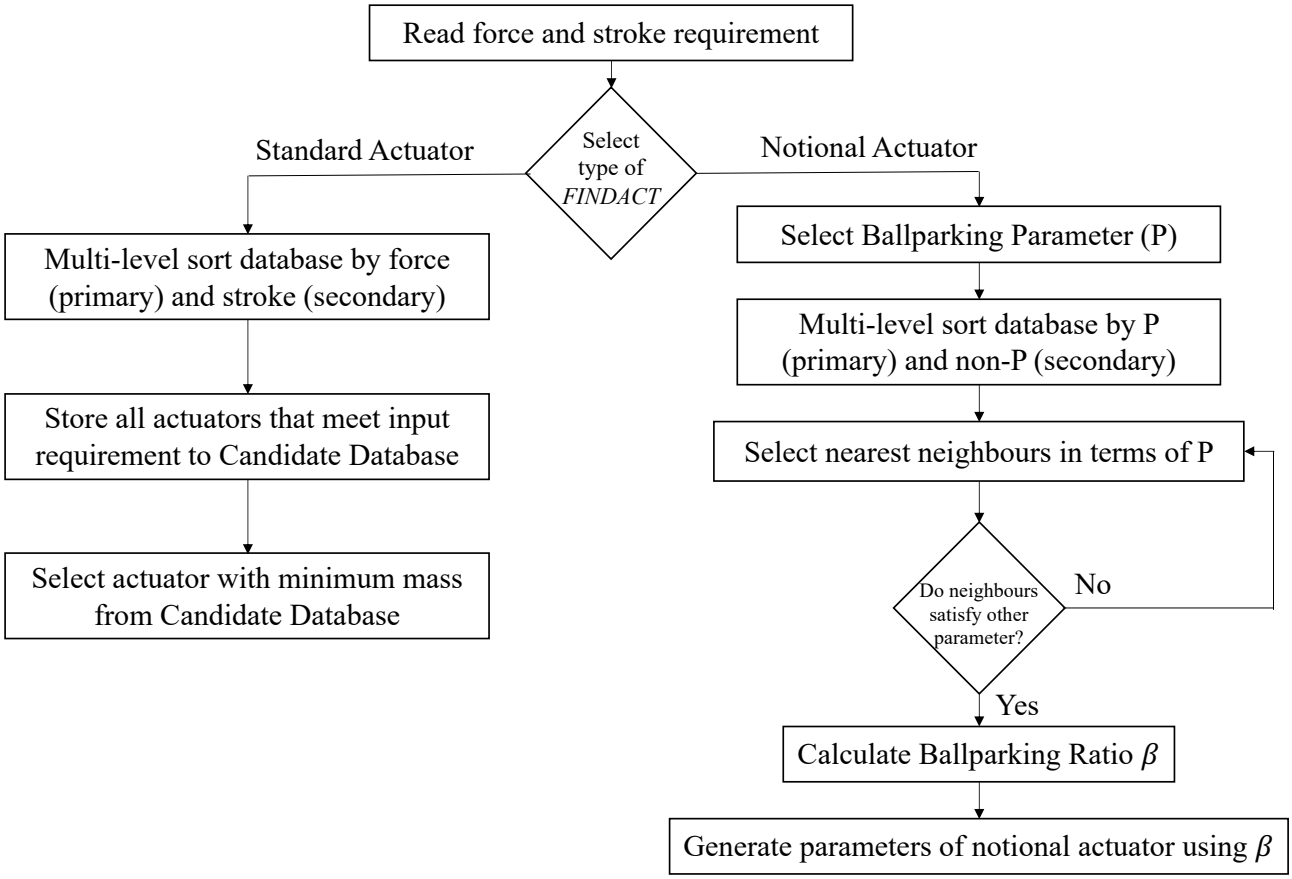


Figure 2 – *FINDACT* algorithm

3.1 Approach 1: Direct selection of a Standard Actuator

Two selection approaches are built into *FINDACT*, the choice of which is with the user. In the first approach, the algorithm simply selects the best possible fit from among the actuators in the database, with minimum weight. A multi-level sort is performed on the database. This means that it is first sorted in ascending order for stroke and wherever strokes of two members are found equal, they are sorted by force in ascending order. The sorted database is now filtered into a candidate database which includes only the members which have stroke and load greater than the input requirement. Finally, the actuator with the minimum value of weight is selected from this.

3.2 Approach 2: Ballparking for Notional Actuator selection

In the second approach, rather than limiting to actuators already present in the database, a notional actuator can be created with the exact specifications required. This is beneficial because it can correctly size the notional actuator when the next best actuator in the database is drastically lighter or more compact at a slight expense of specification.

In a *GENENG*-inspired approach, *FINDACT* performs "ballparking", which is an interpolation based algorithm. One of the input search parameters (stroke or force) is chosen by the user as the ball-parking parameter P. The choice depends on the order of importance of the input parameters to the particular problem. Let P_{req} be the required value of the ballparking parameter. Two actuators with parameters P_1 and P_2 are selected from the sorted database which have the closest match to P_{req}. By comparison, a check is performed so that these members also satisfy the other (non-ballparking) input parameter. Next, a ballparking ratio ϕ is determined according to the relation 1.

$$\phi = \frac{P_{req} - P_1}{P_2 - P_1} \tag{1}$$

This gives the interpolated position of the P_req between its two closest matches P_1 and P_2. Finally ϕ is used to generate the output parameters (weight and closed length) for the notional actuator. Thus, *FINDACT* can be used to estimate the size and weight of actuator, using only basic input like stroke and force required, while being agnostic to other implicit design variables. Knowing the space occupied by the actuator and its span-wise position in the wing from geometry, the wing fuel tank volume loss is computed, and its impact on Endurance can now be examined.

3.3 Jerky results with selection and ballparking approaches

It was found that *FINDACT* led to discontinuous results in Endurance and MTOW for various cases of morphed wing-span as shown in Figure 3. On investigation, it was found that the database is not smooth in terms of weights of various members. It contains spikes in data where weight varies greatly for a small variation in stroke as shown in Figure 4.

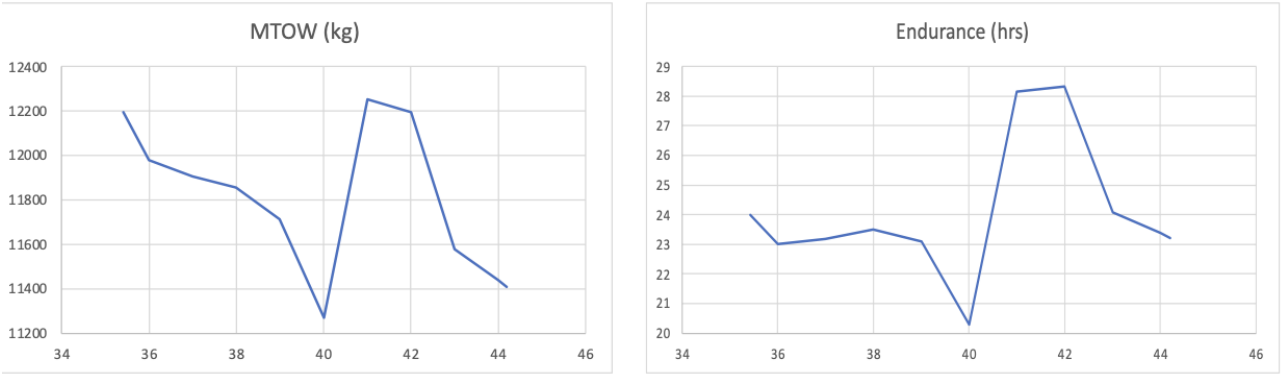


Figure 3 – Jerky results due to ballparking model for various morphing spans

3.4 Linear Fit model

Various mathematical fits were attempted to address the issue of jerky results due to ball-parking. An exponential function led to a poor fit (R^2 = 0.51). A linear fit (R^2 = 0.7778) and a fifth order polynomial improved the situation (R^2 = 0.8066) but the fit is still not a good one. However, when the data is sorted by manufacturer, it is found that each manufacturer has actuators in a particular range of stroke. Therefore, three out of twelve manufacturers are retained in such a way that the entire stroke range from 0 to 7.7 m is covered. The spikes are seen to result from multi-stage actuator designs. To remove the spikes, only 2-stage actuators are considered. Now a linear fit becomes possible. The quality of a linear fit is found to be equivalent to other mathematical fits and is hence considered for simplicity. Figure 4 depicts the linear fit.

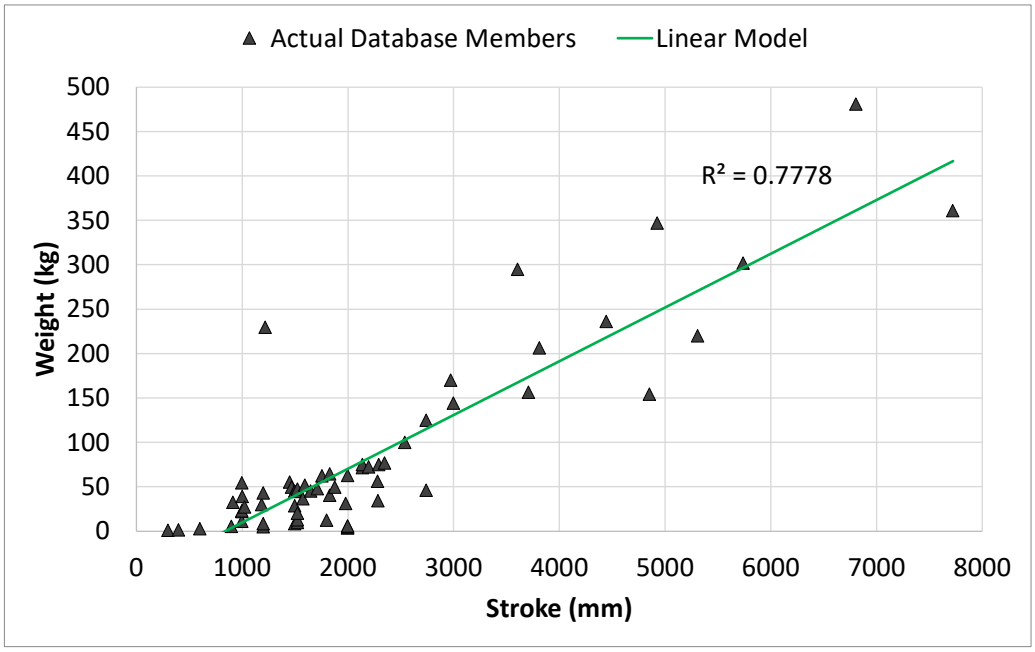


Figure 4 – Linear fit for complete actuator database

3.5 Piecewise Linear Fit model

A piecewise linear fit is also proposed to fit the data in a better fashion. The resulting fit is shown in Figure 5. The entire stroke range is divided into three intervals and the interval points correspond to real actuators selected from the database. It was found that each part corresponds to the catalogue of a single manufacturer – *Univer* (Pneumatic), *Southern* and *Parker* (both Hydraulic) respectively)[13, 14, 15]. The interval points are summarised in Table 3.

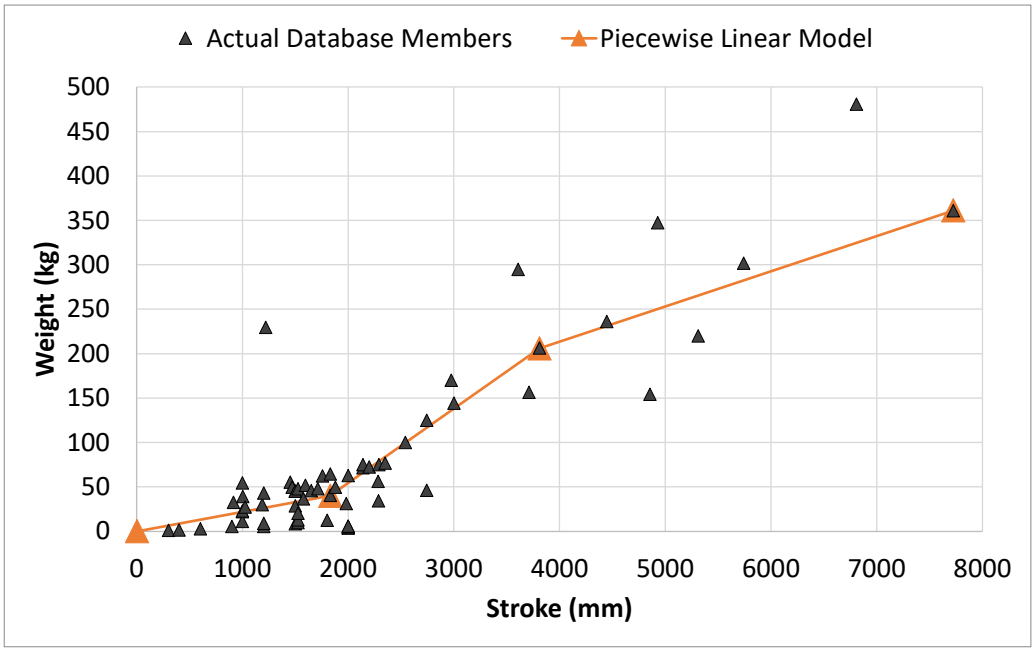


Figure 5 – Piecewise linear fit for complete actuator database

4. DESACT Methodology for Actuator Sizing

On observing the actuator database, it is noted that there is a fairly large variance in the actuator mass even for a given force and stroke. Hence, a different method was also considered to compare a first-principle machine design approach with the results of *FINDACT*.

Table 1 – Piecewise linear actuator model : Interval points

Stroke (mm)	Weight (kg)	Space Occupied (mm)	Force (kg)
0	0	0	0
1829	40	1159	4282
3810	206	1797	7105
7722	361	3070	18889

In the *DESACT* approach, a hydraulic or pneumatic cylinder is designed to meet the design requirements in a customised manner using established machine design methods. From the database trends, it is observed that in general, pneumatic actuators are the lighter option but they are not available for stroke higher than 2 m. Therefore, for stroke requirement greater than 2 m, hydraulic actuators are considered.
A standard double-acting cylinder design methodology is used. The piston-rod assembly diameter is first designed to meet the force requirement. The design cylinder pressure is taken as 10 bar (1e6 Pa) for pneumatic, and 2000 psi (4.7e7 Pa) for hydraulic design. These values are taken from the database, because they reflect prevalent industry practice for certifiable on-board equipment. A three-stage design concept is assumed since this is the trend seen from the database for both categories of actuator. The wall thickness and outer diameter of the cylinder assembly is calculated and the length of the piston-rod assembly is taken to be 15% higher than the stroke. The mounting is assumed to be flange-type for which thickness is calculated. All these parameters are calculated as per machine design thumb rules and first principles [16]. The total mass of the actuator is now calculated by adding up the mass of the piston-cylinder assembly, fluids (such as hydraulic oil) and flange mount. An additional 10% is added to account for pipes, fittings, cables and fasteners.
The *DESACT* actuator model is validated against members of the database. After taking an average over the entire database, the match for 3-stage actuators was found to be within 5% for mass and 10% for closed length. Table 2 summarises the results validation for one representative hydraulic and pneumatic actuator each.

Table 2 – Comparison of *DESACT* Approach with Database for two Representative Actuators

Type	*Hydraulic*		
Force (N)	9658		
Stroke (mm)	2998		
	From Database	By *DESACT*	% difference
Mass (kg)	144	142	1.4
Closed length (mm)	1486	1640	-9.4
Type	*Pneumatic*		
Force (N)	1076		
Stroke (mm)	1200		
	From Database	By *DESACT*	% difference
Mass (kg)	5.4	5.24	3.1
Closed length (mm)	538	597	-9.9

5. Results and Discussions

As a benchmarking exercise, the *FINDACT* and *DESACT* models were used to estimate the mass of actuator for a High Altitude Long Endurance (HALE) Unmanned Aerial Vehicle (UAV) with a span-extending wing with requirements specifications listed in Table . A Morphing Endurance estimation framework was implemented as per previous methods [17], which added the actuator weight to the

empty weight of the UAV, estimated the actuation forces required for span extension, updated drag and aerodynamic efficiency as per increasing span and iterated all these parameters until convergence was achieved.

Table 3 – Morphing Wing Parameters used for Comparison of *FINDACT* and *DESACT*

Parameter	Value
Baseline Wingspan	35.4 m
Maximum Morphed Wingspan	44.2 m
Root Chord	2.2 m
Tip Chord (baseline)	0.58 m
Baseline MTOW	12100 kg
Baseline wing weight	1064 kg
Rate of span morphing	0.5 m/s

5.1 Actuator Selection by FINDACT

There is a choice of fitting either a Piecewise Linear model (in which there are three distinct linear correlations for the actuator weight and space occupied) or a Uniform Linear model (which has a single linear correlation across the entire database of all actuators). Results for MTOW and Endurance are compared for the two models in Figure 6 and Figure 7.

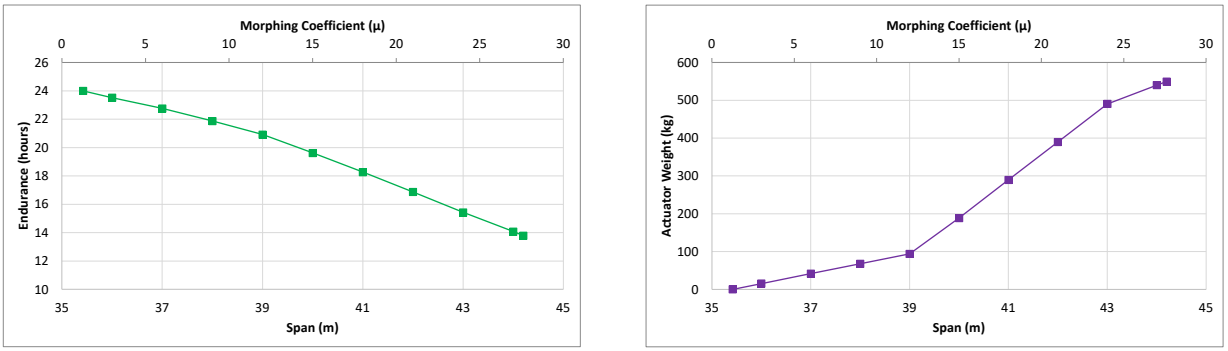


Figure 6 – Morphing results for Piecewise Linear actuator model

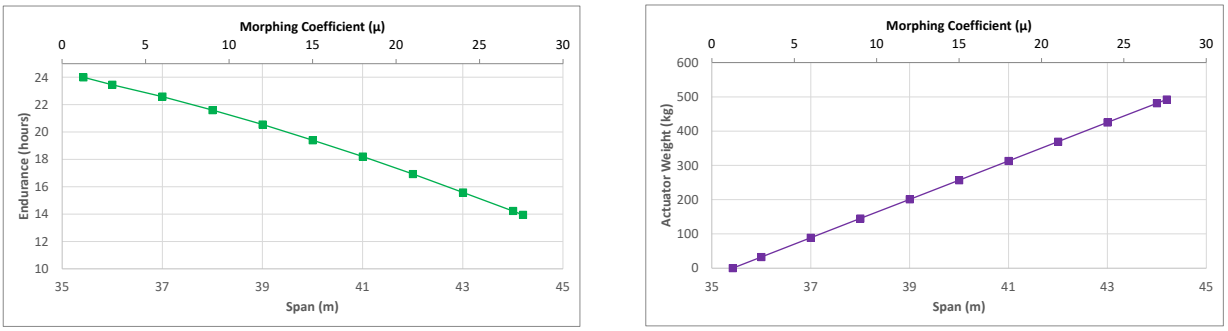


Figure 7 – Morphing results for Uniform Linear actuator model

5.2 Actuator Design by *DESACT* Approach

Results for MTOW and Endurance for *DESACT* are shown in Figure 8. It can be observed that the Endurance benefit improves compared to the case of *FINDACT*.

A comparison of actuator weight results from *FINDACT* and *DESACT* is also shown in Figure 9. It can be seen that there is a major difference in the sizing of actuators for the same span. This is attributed to the fact that *FINDACT* relies on the properties of commercially available actuators

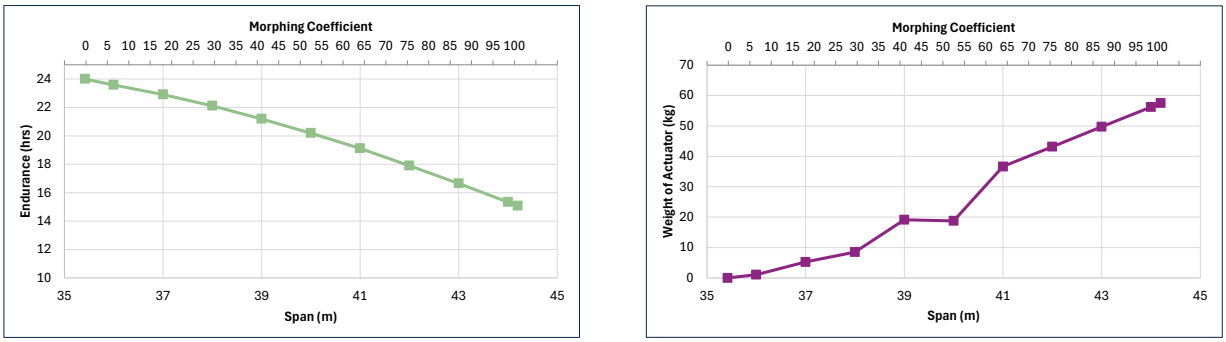


Figure 8 – Morphing results for *DESACT* Actuator Model

for selecting an actuator. The demand on force for morphing is low, in the order of 400 N for the maximum morphing case, whereas COTS actuators for such long stroke are in the order of 4000 N. Due to this, the algorithm tends to oversize the actuator. This is an important learning for span morphing, showing that custom actuator development is needed for this application. Customised actuators will result in slightly better benefit due to morphing.

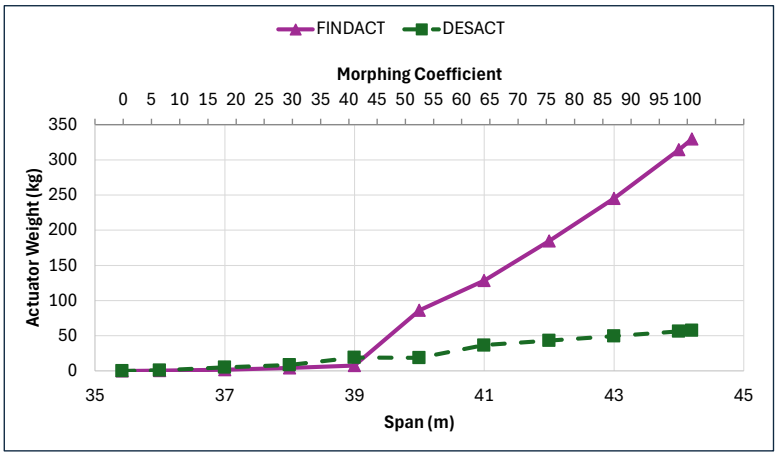


Figure 9 – Comparison of actuators sized for varying morphing coefficients - *FINDACT* versus *DESACT*

6. Conclusions

Two models are presented for estimation of actuator weight and size, namely *FINDACT* and *DESACT*. On comparison, it is found that *FINDACT* is skewed in favour of large force, large stroke actuators while *DESACT* provides better correspondence to force and weight actually required for span extension. This shifts the scales in favour of the use of *DESACT* for span morphing system design frameworks.

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