AN ESTIMATOR FOR AIRCRAFT ACTUATOR CHARACTERISTICS USING SINGULAR VALUE DECOMPOSITION

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ABSTRACT

This paper illustrates how Singular Value Decomposition (SVD) and regression analyses can be used to create estimation models for aircraft actuator components by use of industrial data. The estimation models are at the end used to show how an electromechanical actuator´s weight and size will evolve with respect to output force. An essential step in the early design of aircraft is to be able to predict the weight and size of a resulting concept. This weight and size typically include contributions of main components such as wing and fuselage. Weight and size estimations at this stage can also range down to components at a sub-system level, for example, the aircraft actuators. The weight and size of an actuator depends on many parameters, and it is desirable to understand any underlying relationship to make qualified estimations of an actuator's characteristics. However, the knowledge about a design is often limited at an early design stage and the required information is not always available. Consequently, estimations must be made from limited information and desired properties of the actuator. One way to approach this problem is to use SVD. An SVD analysis determines the most influential parameters in a data set and uses these to create an estimation model that only requires a few inputs for estimating the remaining parameters in the data set. An SVD can thereby be used for both identifying the driving parameters in a statistical dataset of existing solutions and to estimate the characteristics of new designs to be developed.
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Keywords: *Aircraft Actuation System, Singular Value Decomposition, Statistical Analysis, Estimation Model, Principal Component Analysis*

INTRODUCTION

The aircraft actuation system is one of the most critical systems in an aircraft. The most common actuator technology with high maturity and safety is the servo-hydraulic actuator. Today, electrification of the actuation system is emerging and has been shown promising, where the electromechanical- and the electro-hydrostatic actuators are the most common solutions. Benefits in energy consumption, maintenance and in some cases system weight has been reported. [1] [2] [3]

System weight and size are directly related to cost, performance and fuel burn of an aircraft, especially for fighter aircraft. The size and weight of an aircraft actuator is typically dependent on many different parameters, such as required maximum force, speed, acceleration, redundancy level and thermal time constant. Also, the chosen technology will highly influence the size and weight, where the relationship to the previously mentioned parameters may be different. This can make the selection of technology, with regards to size and weight, dependent on, for example, the required maximum force.

Both size and weight are essential parameters when it comes to the early design of an aircraft and are directly tied to the overall results of the sizing procedure for a new aircraft to be developed. It is consequently important to be able to estimate the weight of the actuation system of an aircraft as early as possible in the design process. However, information about a new design is typically scarce at such a stage and this creates a desire of being able to estimate the characteristics of the actuators with limited information. At a conceptual design stage of a new aircraft platform, the desired aircraft performance and wing geometry to fulfil the given operational requirements should at least be known. From this, it should be possible to derive the maximum hinge moments and roll rates of the aircraft, which in turn can be derived to required force and speed of the actuators. Thereby, a desired model to estimate size and weight of the actuators is presented in Figure 1.

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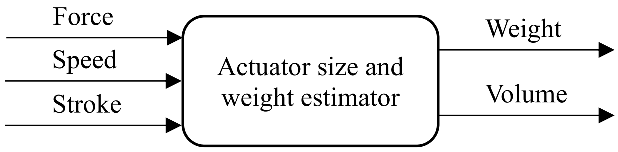

Figure 1: Outline of the desired estimation model.

The main power converters in most electromechanical actuators (EMAs) designed for flight applications are a power electronics control unit (PECU), an electric motor, a ball screw and in some cases a gearbox in between the ball screw and electric motor. There are also many other components and elements needed, such as extra bearings, anti-rotation devices and in some cases brakes. These components include many different parameters which in some sense will affect the final weight and size. The main drivers for size and weight are however the main power converters, i.e., the electric motor, ball screw and gearbox. Previous research provides thorough frameworks for estimation of actuator size and weight, but often much information about the final product is required, and the frameworks often aims at optimizing designs rather than providing simple frameworks for first estimations of size and weight based on limited information. [4] [5] [6] [7]

Objectives

This work aims to provide estimation models for an electromechanical actuator which can be used at an early aircraft conceptual design phase for technology comparisons and selections. The purpose is to use the estimation models for high level comparison of actuators based on the few inputs seen in Figure 1, and to analyse how electromechanical actuators will change in size and weight with respect to the requirements.

Since there is little information publicly available for flight actuators, industrial data will be used to find the relationships between size and weight, and the set inputs shown in Figure 1, for the different components within an EMA. The estimation models will then be used to compile an architecture of an electromechanical actuator where the inputs, which primarily is the maximum output force, will be varied to show how the total weight and size change.

Overall, the long-term objective of this work is to understand whether it may be feasible or not to use electric actuators for a certain platform with respect to size and weight. Today, there is insufficient data present within literature to answer this. This, combined with the lack of high-level estimation methods emphasizes the objectives of this paper.

Additionally, this paper aims to illustrate how a Singular Value Decomposition (SVD) analysis can aid in the identification of principal actuator parameters from statistics of existing solutions and how these can be used to create estimation models that only require a few input parameters. The theoretical fundamental section of this paper describes the underlying theory of an SVD analysis, and some information about the actuator components, while the results and analysis section illustrate the applicability on a data set of existing solutions. The discussion section highlights some alternative approaches and expands on possible opportunities for future work and next steps for this analysis.

THEORETICAL FUNDAMENTALS

This section mentions and elaborates on the approaches and methods that make up the theoretical fundament of this presented work.

Singular Value Decomposition

A Singular Value Decomposition (SVD) utilizes statistical data in order to create estimation models and to improve the understanding of relationships between involved parameters [8]. This is similar to, for example, statistical analyses based on linear regressions. However, a key feature with an SVD is that only a few input parameters are required. This means that all parameters in a data set can be estimated with reasonable accuracy with only a limited number of known or desired parameters. The reason for this is that an SVD builds upon a Principal Component Analysis (PCA) and the dominating parameters in a used data set are thereby identified [9]. An SVD analysis can consequently be used to provide quick estimates of new designs from limited information and to show the dominating relationships between involved parameters. Designs suggested by the SVD model can thereafter be investigated in detail and then possibly be added to the original data set that the SVD once was based on. Similarly, an SVD can also act as a meta model, in for example, optimizations to reduce the computational effort.

Actuator fundamentals

As mentioned in the introduction, an EMA generally consists of at least a PECU, an electric motor and a ball screw. This is illustrated in Figure 2. The weight- and volume studies will be based on this architecture, where a trendline with respect to the inputs mentioned in the introduction is of interest. However, in this work, the PECU will not be included. The focus will thereby be on finding estimation models for the electric motor and the ball screw.

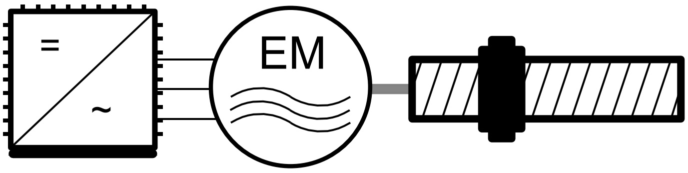

Figure 2: The studied actuator architecture.

The final EMA estimation models for size and weight will be structured as equation (1) and (2).

$$V_{EMA} = \mathrm{V_{BS}}(\mathrm{F,S}) + \mathrm{V_{em}}(\mathrm{T}) \tag{1}$$

$$m_{EMA} = m_{\mathrm{BS}}(\mathrm{F,S}) + m_{\mathrm{em}}(\mathrm{T}) \tag{2}$$

Where V is the volume, F is the force, S is the stroke, T represents torque and m is the mass. The notation BS stands for ball screw and em stands for electric motor.

Ball screw fundamentals

A ball screw is used for transformation of rotational- into linear-mechanic power. A schematic view of a ball screw is presented in Figure 3. The ball screw estimation models for size and weight will be structured as equation (3) and (4).

$$V_{BS} = A_s(F) * (l_{stroke} + l_{nut}(F)) + V_n, V_n = l_n(F)\frac{\pi(d_n^2(F) - d_S^2(F))}{4} \tag{3}$$

$$m_{BS} = m_{sm}(F) * (l_{stroke} + l_{nut}(F)) + m_n(F) \tag{4}$$

Where A_s is the cut-through shaft area, l is length, V_n is the nut volume, $d_{n,S}$ is the nut and shaft outer diameters, m_{sm} is the shaft mass per meter and m_n is the nut mass.

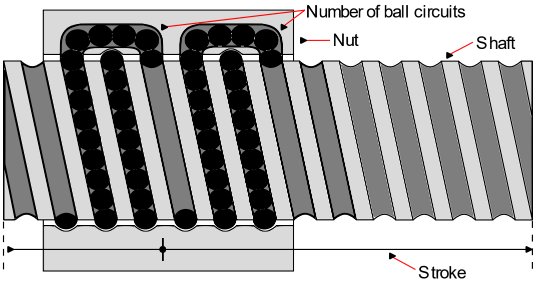

Figure 3: A schematic view of a ball screw.

Electric motor

Previous research has shown that the size and weight of an electric motor can be estimated from motor torque [5]. The torque that the electric motor needs to fulfil can be calculated with equation (5). [10]

$$T = F\frac{L}{2\pi\eta} \tag{5}$$

Where L is the screw lead, η is the screw efficiency, and F is the load force acting on the nut. The torque can thereby be minimized through minimizing the lead, which in turn should minimize the size of the electric motor. The electric motor estimation models for size and weight will be estimated with torque as input which can be calculated from the force requirement with equation (5).

METHODOLOGY

The used methodology in this work is presented in Figure 4. First, the necessary data was gathered from well-known component manufactures. When sufficient data had been found, regression analyses were used to find the relationship between inputs, size and weight for the electric motors. For the ball screw size and weight estimation, SVD analyses were used since many different parameters had to be estimated from very few inputs.

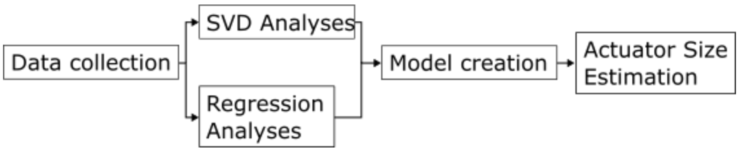

Figure 4: The used methodology and workflow to arrive at an estimator model for actuator sizes.

Subsequently, the component estimation models were connected to create an actuator architecture according to Figure 2. This was thereafter used to study how weight and size evolved with the inputs according to industrial data.

RESULTS AND ANALYSIS

To perform the SVD- and regression analyses, statistics of existing electric motors and ball screws had to be gathered and compiled. The ball screw data was collected from THK, where their caged ball and precision ball screws were selected (SBN, BNFN). [11] The gathered parameters from these specifications were:

- Shaft diameter, lead and mass per length
- Number of closed ball circuits in nut
- Static load rating of ball screw
- Nut volume and mass

With this data, an SVD analysis was performed in Microsoft Excel using an implemented macro. The obtained statistical values were converted into log scale before the SVD analysis. The reason for this was to obtain a better structure of the model due to the size difference of the entries in the collected data set.
The results of the analysis and resulting SVD model can be seen in Figure 5. The four leftmost columns in Figure 5 shows that the "*SBN 1604-5*" reference ball screw from the data set is estimated with zero percent relative error for every variable in the SVD model. The reason for this is that all SVD variables are used and that the ball screw is included in the used data set. However, as mentioned before, one of the benefits with an SVD model is that only a few input parameters are required, and many of the SVD variables in the right-hand side column marked in yellow can consequently be set to zero. The "*w-diagonal*" column on the right side in Figure 5 indicates the significance of the different variables, and it can be seen that the most significant variables for the estimation model are the once corresponding to outer shaft diameter, screw lead and the number of recirculating circuits of balls. Consequently, all SVD variables except the ones in the first three rows are set to zero to create an estimation model that only require three inputs. This reduced SVD model can be seen in Figure 6. The maximum relative error of the estimation has now increased to 20% as seen in the second leftmost column. The largest difference comes from the dynamic load rating while all other parameters are estimated with little difference. Only three parameters are thereby used to estimate the remaining 10 from the data set within 20% relative error.

	Rel error	SBN 1604-5	Estimate	Adjusted	Result	Average														SVD variables	w-diagonal	residual
Outer diameter shaft	0,00	16,00	16,00	1,20	-0,48	1,68	0,177	-0,027	0,002	-0,019	0,011	-0,002	0,005	-0,002	0,007	-0,003	-0,001	0,005	0,002	-2,72	9,11	75,14
Lead	0,00	4,00	4,00	0,60	-0,44	1,04	0,143	0,041	-0,112	0,002	-0,021	-0,020	0,008	0,015	0,001	-0,003	0,000	0,000	-0,001	-0,53	2,86	0,42
Number of circuits	0,00	1,00	1,00	0,00	-0,17	0,17	0,057	0,122	0,136	0,004	-0,021	-0,012	0,004	0,001	0,010	-0,001	0,000	-0,001	-0,001	0,13	1,65	0,21
Dynamic load rating	0,00	5,30	5,30	0,72	-0,98	1,70	0,302	0,132	-0,028	0,038	0,024	-0,014	0,010	-0,002	0,002	0,006	0,000	0,000	0,001	-0,66	0,79	0,20
Static load rating	0,00	8,00	8,00	0,90	-1,22	2,12	0,403	0,143	0,035	0,010	0,023	0,000	-0,008	0,001	-0,011	-0,005	0,000	0,000	-0,001	-1,56	0,53	0,15
Nut outer diameter	0,00	36,00	36,00	1,56	-0,41	1,97	0,149	-0,011	-0,017	-0,010	0,006	0,005	0,010	-0,006	0,003	-0,002	0,002	0,003	-0,002	0,74	0,39	0,15
Nut flange diameter	0,00	59,00	59,00	1,77	-0,36	2,13	0,134	-0,003	-0,024	-0,010	0,006	0,002	0,003	-0,009	0,007	-0,004	0,000	-0,004	0,004	-1,90	0,32	0,17
Nut lange width	0,00	11,00	11,00	1,04	-0,23	1,27	0,107	0,012	-0,048	-0,002	-0,002	-0,015	-0,031	-0,009	0,007	0,001	0,000	0,001	-0,001	-1,05	0,26	0,06
Nut length	0,00	53,00	53,00	1,72	-0,50	2,23	0,184	0,119	0,004	-0,008	-0,027	0,015	-0,009	0,009	-0,003	0,002	0,001	0,002	0,004	1,58	0,19	0,06
Shaft inertia per length	0,00	0,00	0,00	-7,30	-1,88	-5,42	0,731	-0,205	0,032	0,039	-0,014	0,001	-0,001	0,001	-0,001	0,000	0,000	0,000	0,000	1,53	0,09	0,02
Nut mass	0,00	0,42	0,42	-0,38	-1,20	0,82	0,442	0,097	-0,052	-0,024	-0,015	0,021	0,006	-0,010	0,002	0,002	-0,001	-0,001	-0,002	0,07	0,02	0,01
Shaft mass/meter	0,00	1,35	1,35	0,13	-0,95	1,08	0,364	-0,054	0,033	-0,070	0,017	-0,012	-0,001	0,010	-0,001	0,003	0,000	-0,001	0,000	-0,75	0,06	0,01
Turns	0,00	2,50	2,50	0,40	-0,01	0,40	-0,005	0,002	-0,010	0,016	0,024	0,024	-0,007	0,017	0,011	0,000	0,000	-0,001	-0,001	-1,01	0,06	0,01
	0,00																					

Figure 5: The Singular Value Decomposition (SVD) model of the ball screw.

	Rel error	SBN 1604-5	Estimate	Adjusted	Result	Average														SVD variables	w-diagonal	residual
Outer diameter shaft	0,03	16,00	16,44	1,22	-0,47	1,68	0,177	-0,027	0,002	-0,019	0,011	-0,002	0,005	-0,002	0,007	-0,003	-0,001	0,005	0,002	-2,72	9,11	75,14
Lead	0,04	4,00	4,14	0,62	-0,43	1,04	0,143	0,041	-0,112	0,002	-0,021	-0,020	0,008	0,015	0,001	-0,003	0,000	0,000	-0,001	-0,53	2,86	0,42
Number of circuits	0,07	1,00	0,93	-0,03	-0,20	0,17	0,057	0,122	0,136	0,004	-0,021	-0,012	0,004	0,001	0,010	-0,001	0,000	-0,001	-0,001	0,13	1,65	0,21
Dynamic load rating	0,20	5,30	6,37	0,80	-0,90	1,70	0,302	0,132	-0,028	0,038	0,024	-0,014	0,010	-0,002	0,002	0,006	0,000	0,000	0,001	0,00	0,79	0,20
Static load rating	0,13	8,00	9,00	0,95	-1,17	2,12	0,403	0,143	0,035	0,010	0,023	0,000	-0,008	0,001	-0,011	-0,005	0,000	0,000	-0,001	0,00	0,53	0,15
Nut outer diameter	0,02	36,00	36,83	1,57	-0,40	1,97	0,149	-0,011	-0,017	-0,010	0,006	0,005	0,010	-0,006	0,003	-0,002	0,002	0,003	-0,002	0,00	0,39	0,15
Nut flange diameter	0,02	59,00	58,05	1,76	-0,37	2,13	0,134	-0,003	-0,024	-0,010	0,006	0,002	0,003	-0,009	0,007	-0,004	0,000	-0,004	0,004	0,00	0,32	0,17
Nut lange width	0,16	11,00	9,29	0,97	-0,30	1,27	0,107	0,012	-0,048	-0,002	-0,002	-0,015	-0,031	-0,009	0,007	0,001	0,000	0,001	-0,001	0,00	0,26	0,06
Nut length	0,13	53,00	46,10	1,66	-0,56	2,23	0,184	0,119	0,004	-0,008	-0,027	0,015	-0,009	0,009	-0,003	0,002	0,001	0,002	0,004	0,00	0,19	0,06
Shaft inertia per length	0,01	0,00	0,00	-7,29	-1,88	-5,42	0,731	-0,205	0,032	0,039	-0,014	0,001	-0,001	0,001	-0,001	0,000	0,000	0,000	0,000	0,00	0,09	0,02
Nut mass	0,14	0,42	0,36	-0,44	-1,26	0,82	0,442	0,097	-0,052	-0,024	-0,015	0,021	0,006	-0,010	0,002	0,002	-0,001	-0,001	-0,002	0,00	0,02	0,01
Shaft mass/meter	0,02	1,35	1,33	0,12	-0,96	1,08	0,364	-0,054	0,033	-0,070	0,017	-0,012	-0,001	0,010	-0,001	0,003	0,000	-0,001	0,000	0,00	0,06	0,01
Turns	0,04	2,50	2,59	0,41	0,01	0,40	-0,005	0,002	-0,010	0,016	0,024	0,024	-0,007	0,017	0,011	0,000	0,000	-0,001	-0,001	0,00	0,06	0,01
	0,20																					

Figure 6: The reduced SVD model.

As a small validation test, an analysis was made on a ball screw not included in the original data set that the SVD was based on. This was done to see how well the ball screw could be estimated with the obtained model. Here, the three SVD variables were varied in order to minimize the overall difference between the reference and the estimate of the ball screw. The results of this can be seen in Figure 7.

	Rel error	BNFN 10020A-7.5	Estimate	Adjusted	Result	Average														SVD variables	w-diagonal	residual
Outer diameter shaft	0,04	100,00	104,05	2,02	0,34	1,68	0,177	-0,027	0,002	-0,019	0,011	-0,002	0,005	-0,002	0,007	-0,003	-0,001	0,005	0,002	2,00	9,11	75,14
Lead	0,01	20,00	19,88	1,30	0,26	1,04	0,143	0,041	-0,112	0,002	-0,021	-0,020	0,008	0,015	0,001	-0,003	0,000	0,000	-0,001	0,72	2,86	0,42
Number of circuits	0,06	3,00	2,81	0,45	0,28	0,17	0,057	0,122	0,136	0,004	-0,021	-0,012	0,004	0,001	0,010	-0,001	0,000	-0,001	-0,001	0,54	1,65	0,21
Dynamic load rating	0,05	253,80	242,25	2,38	0,68	1,70	0,302	0,132	-0,028	0,038	0,024	-0,014	0,010	-0,002	0,002	0,006	0,000	0,000	0,001	0,00	0,79	0,20
Static load rating	0,02	1105,40	1125,52	3,05	0,93	2,12	0,403	0,143	0,035	0,010	0,023	0,000	-0,008	0,001	-0,011	-0,005	0,000	0,000	-0,001	0,00	0,53	0,15
Nut outer diameter	0,04	170,00	177,58	2,25	0,28	1,97	0,149	-0,011	-0,017	-0,010	0,006	0,005	0,010	-0,006	0,003	-0,002	0,002	0,003	-0,002	0,00	0,39	0,15
Nut flange diameter	0,01	243,00	241,33	2,38	0,25	2,13	0,134	-0,003	-0,024	-0,010	0,006	0,002	0,003	-0,009	0,007	-0,004	0,000	-0,004	0,004	0,00	0,32	0,17
Nut flange width	0,08	32,00	29,43	1,47	0,20	1,27	0,107	0,012	-0,048	-0,002	-0,002	-0,015	-0,031	-0,009	0,007	0,001	0,000	0,001	-0,001	0,00	0,26	0,06
Nut length	0,03	471,00	482,98	2,68	0,46	2,23	0,184	0,119	0,004	-0,008	-0,027	0,015	-0,009	0,009	-0,003	0,002	0,001	0,002	0,004	0,00	0,19	0,06
Shaft inertia per length	0,07	0,00	0,00	-4,08	1,33	-5,42	0,731	-0,205	0,032	0,039	-0,014	0,001	-0,001	0,001	-0,001	0,000	0,000	0,000	0,000	0,00	0,09	0,02
Nut mass	0,08	51,84	56,01	1,75	0,93	0,82	0,442	0,097	-0,052	-0,024	-0,015	0,021	0,006	-0,010	0,002	0,002	-0,001	-0,001	-0,002	0,00	0,02	0,01
Shaft mass/meter	0,08	57,13	61,72	1,79	0,71	1,08	0,364	-0,054	0,033	-0,070	0,017	-0,012	-0,001	0,010	-0,001	0,003	0,000	-0,001	0,000	0,00	0,06	0,01
Turns	0,02	2,50	2,46	0,39	-0,01	0,40	-0,005	0,002	-0,010	0,016	0,024	0,024	-0,007	0,017	0,011	0,000	0,000	-0,001	-0,001	0,00	0,06	0,01
	0,08																					

Figure 7: The validation test and estimation of a reference ball screw.

As seen in Figure 7, the characteristics for the reference ball screw of type *BNFN 10020A-7.5* has been inserted in the third column from the left. The maximum relative error found is consequently around 8% after adjusting the three SVD variables. In this case, the largest difference is found in the *nut flange width* and the *shaft mass/meter* parameters.

It can be assumed that the lead should be as low as possible to reduce the required torque by the electric motor, which should keep the motor as small as possible. Thereby, it is interesting to find the relationships between the ball screw rated load, and all the other parameters, when the lead is kept as low as possible. These relationships can be found by utilizing the SVD estimation model from Figure 7 with the built-in solver in Excel. Characteristics of "yet-to-be-designed" ball screws can thereby be estimated with the three remaining SVD variables. This is done by optimizing their values so that the given requirements are fulfilled as best as possible. The built-in solver in Excel was consequently used for this purpose. The solver's objective function was specified as a minimization of the lead requirement with the three SVD variables as design parameters. The SVD variables were constrained to only vary between -2 and 2 to allow light extrapolation from the original data set (values between -1 and 1 corresponds to an interpolation in an SVD analysis). Additional constraints were subsequently added to account for different requirements on static-load rating and number of circuits. The solver was then used on the SVD model to give estimates for all characteristics under varying requirements and constraints. More specifically, the requirement on static-load rating was varied between 0 and 300kN for each number of circuits requirement, which was specified as either 1, 2 or 3. Consequently, this analysis resulted in 37 different estimated ball screw designs. Figures 8, 9 and 10 shows some of the resulting characteristics for the estimated ball screw designs.

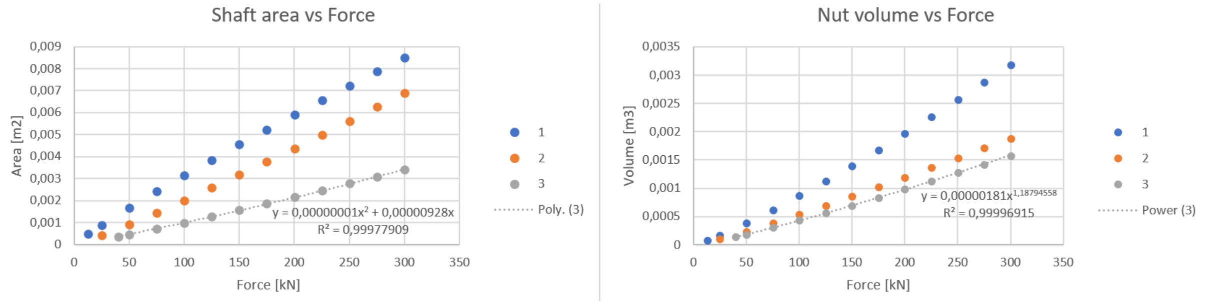

Figure 8: The left graph shows the relationship between force and shaft area and the relationship between force and nut volume is shown to the right.

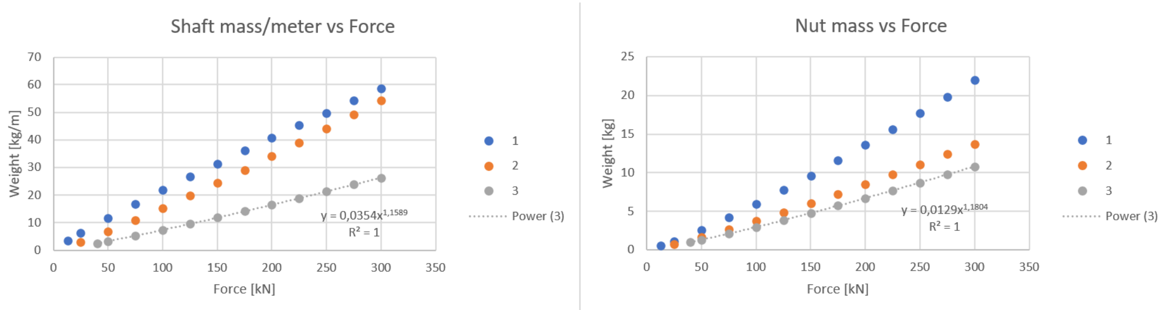

Figure 9: The left graph shows the relationship between force and shaft mass per meter while the relationship between force and nut mass is shown in the right graph.

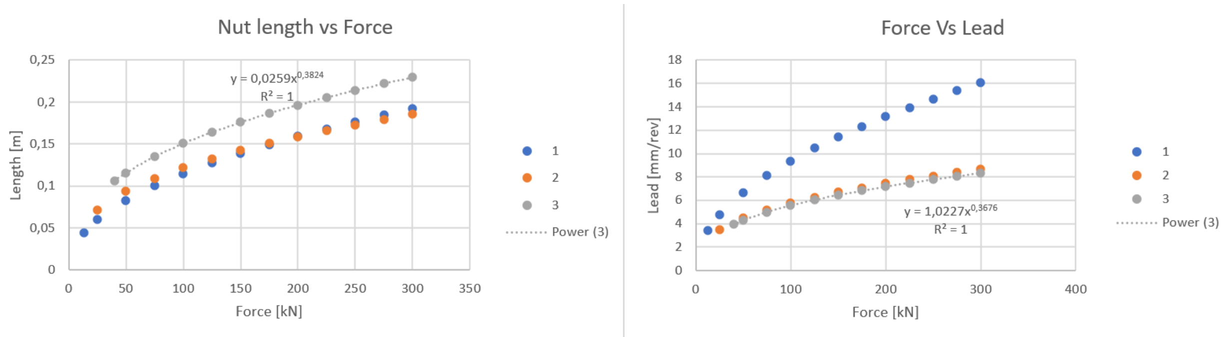

Figure 10: The left graph shows the relationship between force and nut length while the relationship between force and lead is shown in the right graph.

The results from Figures 8, 9 and 10 were thereafter used to create the final estimation model for the ball screws. This was done by fitting exponential trendlines to the presented graphs. However, as seen in Figure 9, the ball screws with 3 rows of balls are generally the lighter options in terms of weight. Consequently, these are of most interest and their corresponding relationships from the trendline fitting are presented below in equations (6-11).

$$m_{sm} = 0{,}0354 * F^{1{,}16}\ [kg/m] \tag{6}$$

$$A_s = 1 * 10^{-8} * F^2 + 9{,}28 * 10^{-6} * F\ [m^2] \tag{7}$$

$$m_n = 0{,}0129 * F^{1{,}18}\ [kg] \tag{8}$$

$$l_n = 0{,}0259 * F^{0{,}38}\ [m] \tag{9}$$

$$V_n = 1{,}8 * 10^{-6} * F^{1{,}19}\ [m^3] \tag{10}$$

$$L = 1{,}023 * \mathrm{F}^{0{,}37}\ [mm/rev] \tag{11}$$

Here, F represents the static load rating in kN.

The electric motor data was collected from Bosch Rexroth, where the selected motor type was a permanent magnet synchronous motor (PMSM) [12]. This motor type is used in aircraft EMAs due to its high-power density, high efficiency and high response.

For the estimation of electric motor size and weight, regression analyses were made to find how weight and volume varies with output torque. For every electric motor size and weight, four output torque levels were specified in the data. These were the *maximum torque* that the motor can produce, and the *continuous torque* which can be held at standstill with a maximum temperature increase of 60 K in the stator when it is cooled by *natural convection, forced convection* or *liquid cooling*. The results of this can be seen in Figure 11 and 12.

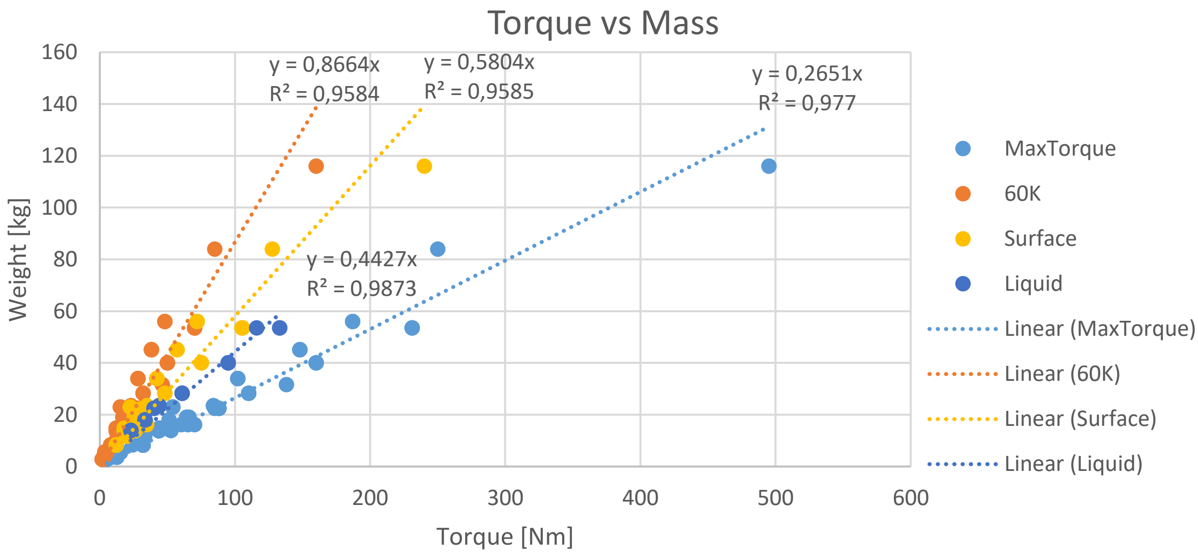

Figure 11: Torque and weight regression analysis of the PMSM data.

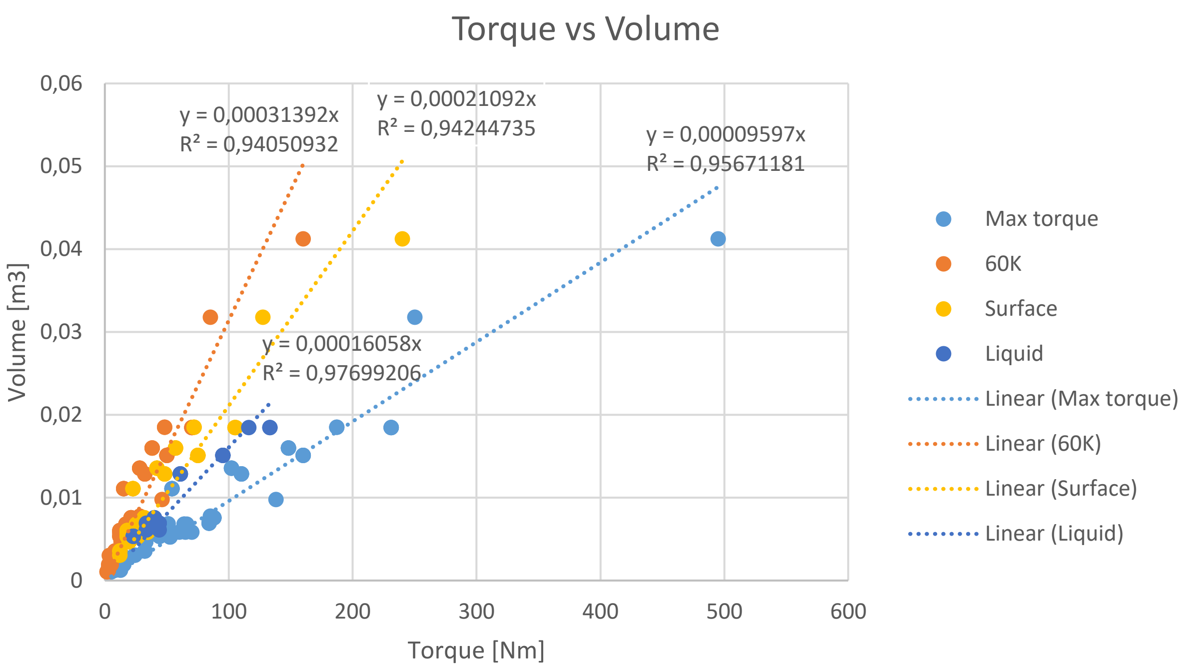

Figure 12: Torque and volume regression analyses of the PMSM data.

The weight and volume estimation models for the PMSM based on the regression analyses are presented in equations (12-19).

$$m_{MaxTorque} = 0{,}265 * T_{Max} \tag{12}$$

$$m_{LiquidCooled} = 0{,}443 * T_{Max} \tag{13}$$

$$m_{FanCooled} = 0{,}580 * T_{Max} \tag{14}$$

$$m_{NaturalConvection} = 0{,}866 * T_{Max} \tag{15}$$

$$V_{MaxTorque} = 9{,}597 * 10^{-5} * T_{Max} \tag{16}$$

$$V_{LiquidCooled} = 1{,}606 * 10^{-4} * T_{Max} \tag{17}$$

$$V_{FanCooled} = 2{,}109 * 10^{-4} * T_{Max} \tag{18}$$

$$V_{NaturalConvection} = 3{,}139 * 10^{-4} * T_{Max} \tag{19}$$

With the estimation models created for the ball screw and electric motor, the total mass and volume of an EMA with a single ball screw and PMSM was estimated with equations (1-5). The results of these models with varying force requirement can be found in Figures 13 and 14.

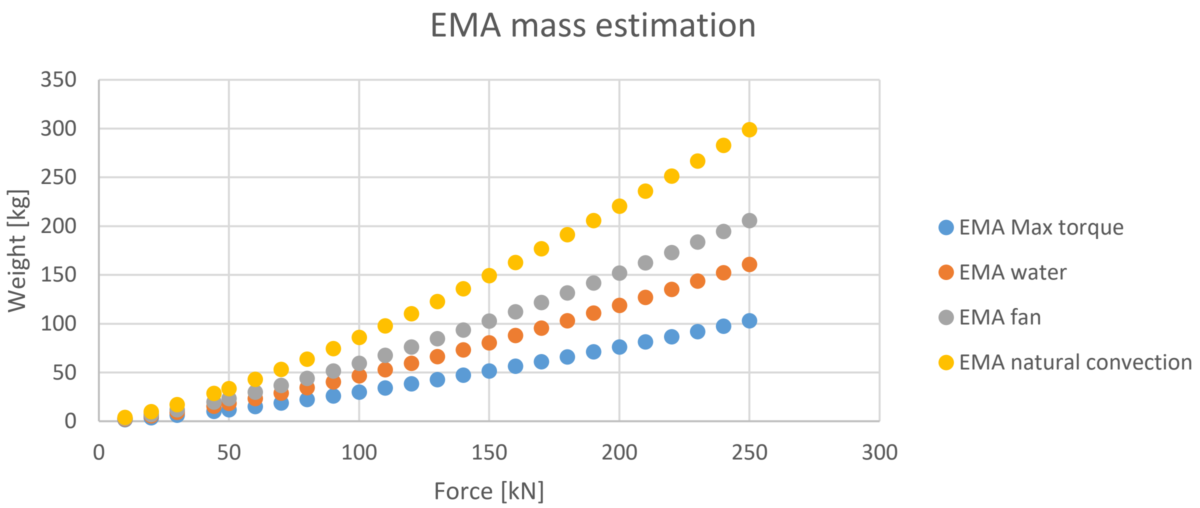

Figure 13: The result of the EMA weight estimation model with varied force input.

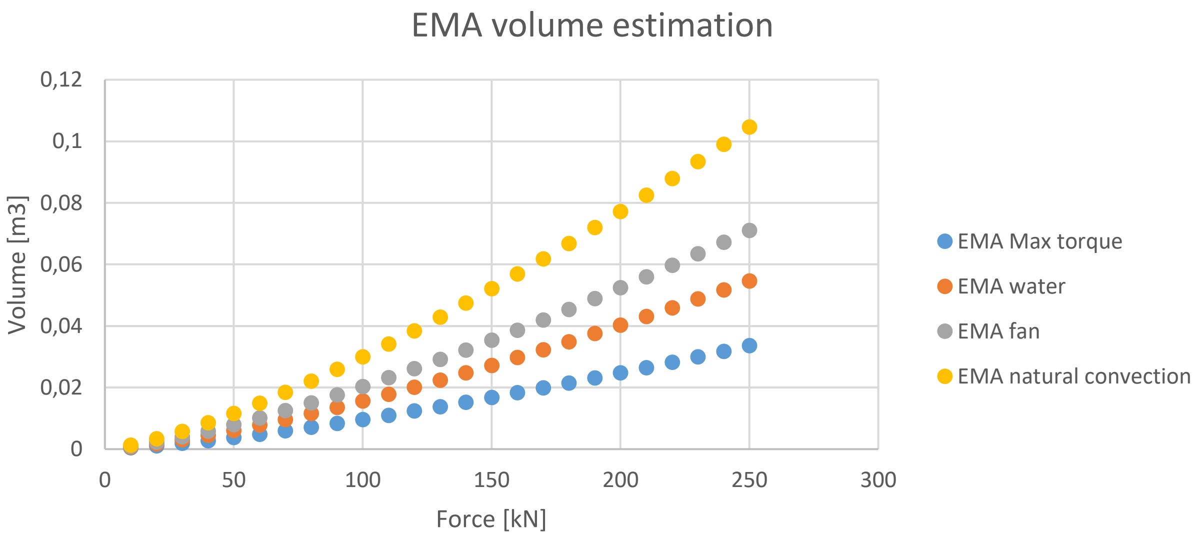

Figure 14: The result of the EMA volume estimation model with varied force input.

DISCUSSION

The results in the previous section have shown how statistics of existing solutions can be used to create estimation models for the design of new actuators. A combination of regression and SVD analyses were used in this study, although, there are many other ways for creating estimation models, such as machine learning techniques. However, such techniques typically offer less transparency compared to, for example, regular regressions between variables and SVD analyses. The SVD analyses were only performed on the ball screw statistics. Regular regression models could have worked in this case as well, however, the relationships between parameters would in that case have to be determined manually. This would have added to the complexity of the method and uncertainty about the estimations.

The validation of the SVD analysis showed good agreement with the reference ball screw's characteristics with the three SVD variables. However, a future validation of the SVD estimation model could involve approximating the characteristics for several ball screws that have been excluded from the used data set and SVD analysis. This could thereby give a better indication of the model's validity over a wider range of ball screw designs. Another possibility is to also create an SVD analysis of the electric motor data. This could possibly ease the design process and an optimization could be used to obtain a complete actuator design automatically, rather than doing it manually.

One of many possible topics for future work is to expand the used datasets to include even more parameters. This could include parameters that are required to set up simulation models for analysis of, for example, performance and power consumption. With such estimation models, actuators could be compared with respect to many attributes at an early stage of aircraft conceptual design, and thereby provide a better decision basis with respect to actuator technologies. An SVD could consequently be used to estimate an even higher number of unknown parameters for a new actuator system than shown in this paper, thus increasing the overall fidelity. The SVD estimations with the solver currently involve some manual labour. Consequently, future improvements of this presented work involve automizing the estimation process. This could, for example, be done with user-implemented macros in Excel together with a design of experiments (DOE) that specifies the different cases that are to be run. A higher degree of automation would also allow for easier continues updates in the underlying data set that the estimations originally are based on. This would therefore ensure that the estimates are up to date if additional information is introduced to the used data set. Consequently, this is a prominent area for future work for the presented study.

Overall, this work is part of a larger scope, where the intention is to compare different actuator technologies, such as electro-hydrostatic-, electromechanical- and servo-hydraulic actuators, with respect to size and weight. The next step within the scope of this work is to use the obtained estimation models to predict the size and weight of an actuator architecture which has been used in an aircraft, and were weight and size is known. Then, it would be possible to compare the estimation with real data and in that way adjust the estimation model to be more accurate.

CONCLUSIONS

This paper has shown how an estimator for aircraft actuator characteristics can be created with statistics and various regression analyses. A Singular Value Decomposition (SVD) was used as a convenient way for identifying the principal components of a used data set and to estimate characteristics from limited information. The results from the performed SVD and regression analyses showed that simple estimation models could be obtained. The results also show that the methodology used in this work can be used to create estimation models of electromechanical actuators with respect to industrial data where growth trends with based on output force and stroke can be found. The estimation models were found to be accurate with respect to the relative errors in the SVD model and the R^2-values in excel. This means that it is possible to estimate size and weight of the actuator components based on limited information, and from this, a good indication of the total size and weight of an aircraft actuator can be found. However, to predict the weight and size of aircraft actuators, the data must be compared and, if found necessary, adjusted with realistic data of physical actuators.

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