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AN ESTIMATOR FOR AIRCRAFT ACTUATOR CHARACTERISTICS USING SINGULAR VALUE DECOMPOSITION

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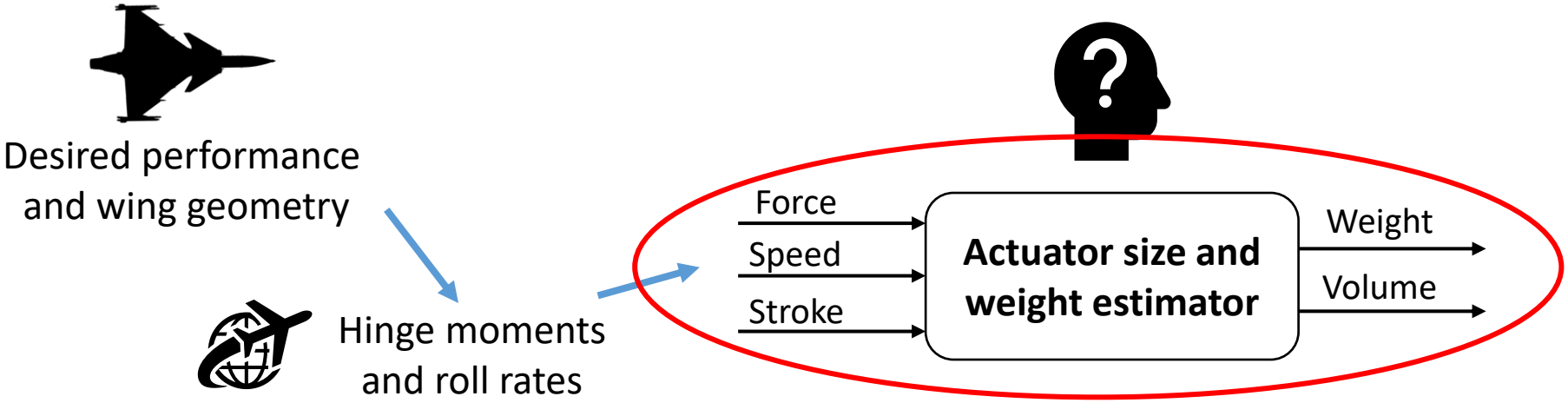
Presentation Outline

- Introduction
- Objectives
- Theory
- Methodology
- Analysis
- Results
- Conclusions and Outlook

Purpose of paper:
Use Singular Value Decomposition (SVD) and regression analyses to create an estimator for the design of aircraft actuator components based on industrial data

Introduction

- Size and Weight are crucial parameters in the early design of an aircraft
- Important to estimate these parameters for subsystems
  - Technology selection
- However, knowledge and available information about a new design is typically scarce at an early conceptual stage
- Desire for being able to estimate actuator characteristics from limited information

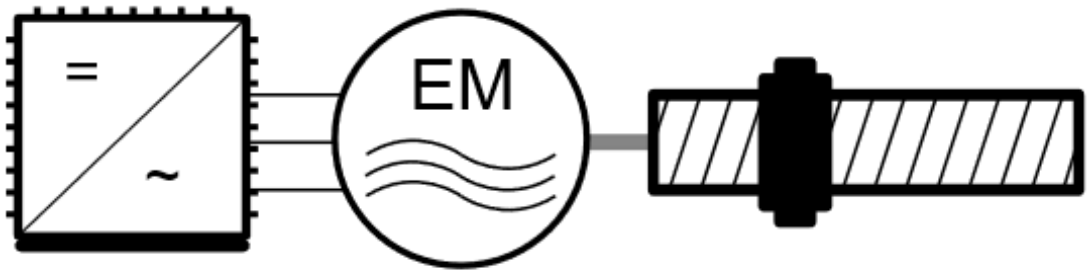


Objectives

- To provide simple estimation models for an EMA to be used in aircraft conceptual design for technology comparision and selection
- Illustrate how weight and size varies with respect to requirements
- How can Singular Value Deomposition (SVD) be used for this purpose and to address the problem of limited information and lack of data?
- Long-term objective:
  - To be able to understand whether it may be feasible or not to use electric actuators for a certain platform with respect to size and weight

Actuator fundamentals

- Electro-Mechanical Actuator
  - Power Electronics Control Unit (PECU)
  - Electric motor
  - Ball screw

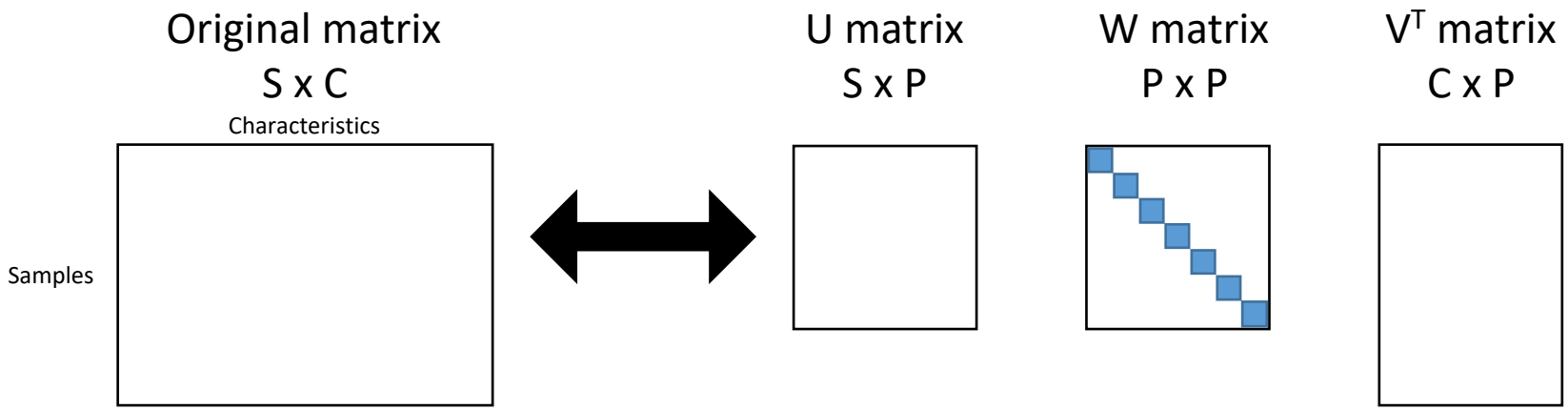


Volume calculation -> $$V_{EMA} = \mathrm{V_{BS}(F,S)} + \mathrm{V_{em}(T)}$$

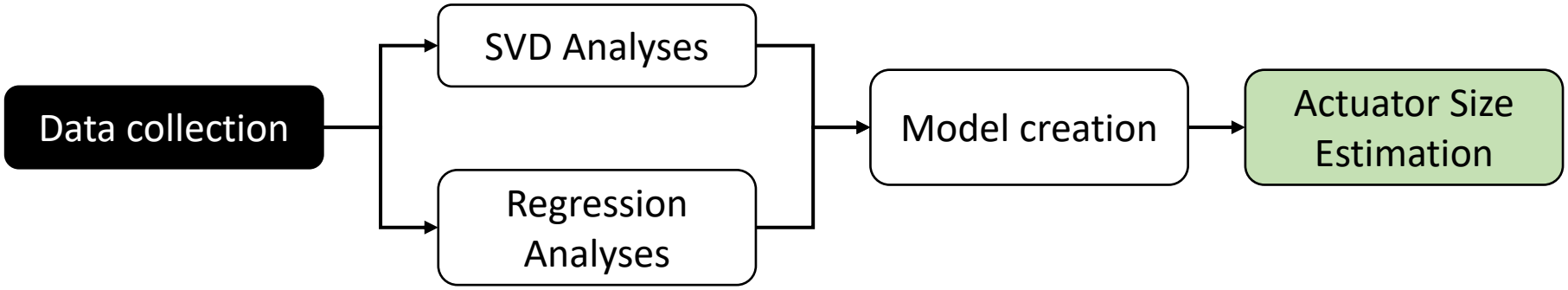
Mass calculation -> $$m_{EMA} = m_{\mathrm{BS}}(\mathrm{F,S}) + m_{\mathrm{em}}(\mathrm{T})$$

Singular Value Decomposition (SVD)

- A statistical analysis that can be used to create estimation models
- Only a few input parameters are needed to make an estimate of the remaining parameters in a data set
- It builds upon a *Principal Component Analysis (PCA)*
- The driving parameters in a data set can be determined and matched against desired or known properties about a system under development
- Quick design estimates can be made based on given requirements and limited information



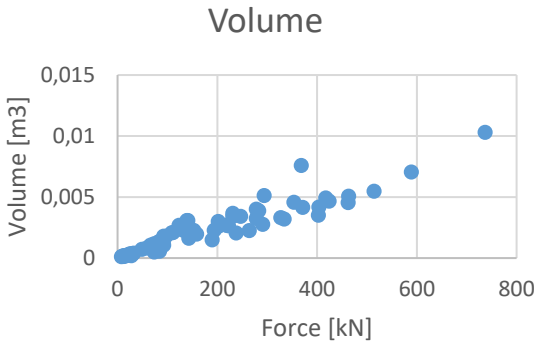
- Method for creating the actuator size and weight estimator:

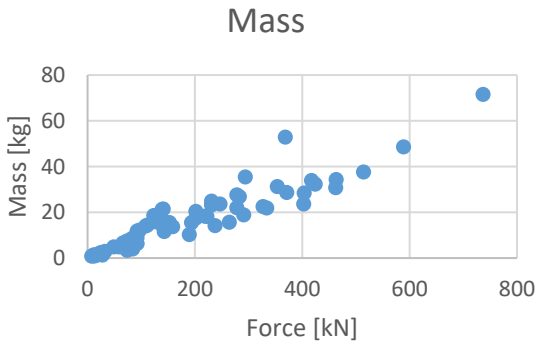


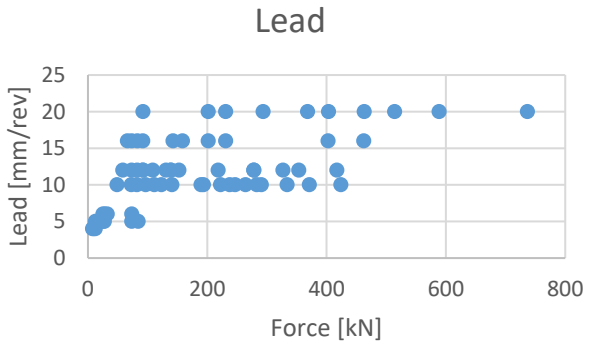
- Gathering of data
- Regression analyses to find relationships between inputs and size and weights for electric motors
- SVD analyses for ball screw size and weight estimation
- Model creation by connecting the component estimation models together

Data gathering

- Statistics of existing ball screws
  - Ball screw data were collected from THK for caged and precision ball screws







SVD Analysis

- Excel implemented macro
- The "*BNFN 10020A-7.5*" ball screw was excluded from the data set for testing purposes later on
- SVD Analysis Model:

	Rel error	SBN 1604-5	Estimate	Adjusted	Result	Average													SVD variables	w-diagonal	residual
Outer dia 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
no 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
Dyn load	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
Stat load	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 out dia	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 dia	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
flange w	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 [kgm2/mm]	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																					

SVD Analysis

- The SVD model

	Rel error	SBN 1604-5	Estimate	Adjusted	Result	Average													SVD variables	w-diagonal	residual
Outer dia 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	0.00	-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	-0.00	-0.53	2.86	0.42
no 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	-0.00	0.13	1.65	0.21
Dyn load	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	0.00	-0.66	0.79	0.20
Stat load	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	-0.00	-1.56	0.53	0.15
Nut out dia	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	-0.00	0.74	0.39	0.15
nut flange dia	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	0.00	-1.90	0.32	0.17
flange w	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	-0.00	-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	0.00	1.58	0.19	0.06
shaft inertia [kgm2/mm]	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	0.00	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	-0.00	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	0.00	-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	-0.00	-1.01	0.06	0.01
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SVD Analysis

- The SVD model

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no 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
Dyn load	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
Stat load	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 out dia	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 dia	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
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shaft inertia [kgm2/mm]	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
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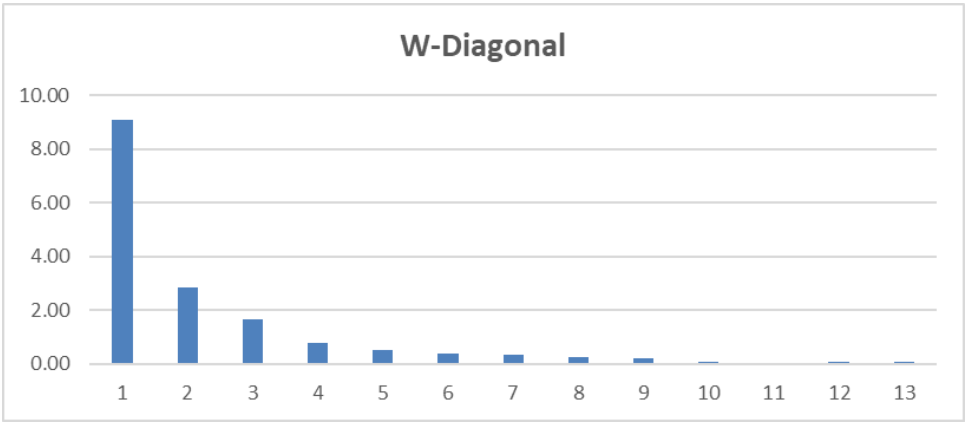
SVD Analysis

- The SVD model



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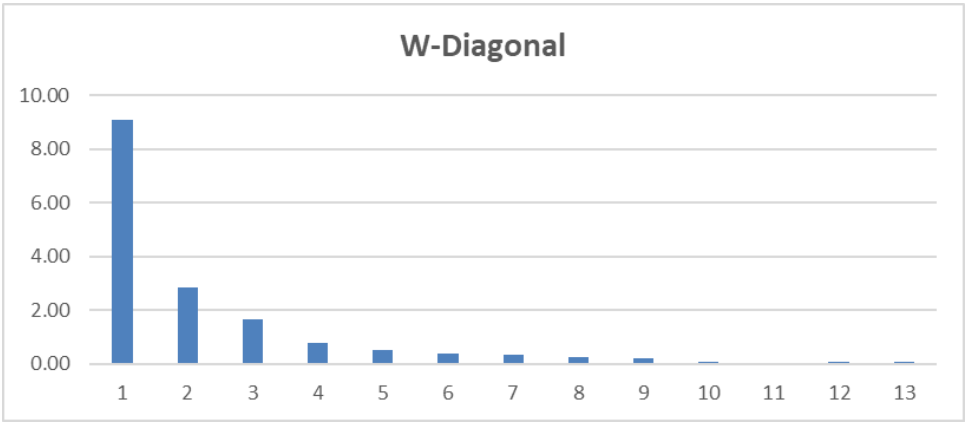
Lead	0.00	4.00	4.00	0.60	-0.44	1.04	0.143	0.041	-0.112	0.002	-0.021	-0.020	0.008	0.015	0.001	-0.003	0.000	0.000	-0.001	-0.53	2.86	0.42
no circuits	0.00	1.00	1.00	0.00	-0.17	0.17	0.057	0.122	0.136	0.004	-0.021	-0.012	0.004	0.001	0.010	-0.001	0.000	-0.001	-0.001	0.13	1.65	0.21
Dyn load	0.00	5.30	5.30	0.72	-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
Stat load	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 out dia	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 dia	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
flange w	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 [kgm2/mm]	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																					

SVD Analysis

- The SVD model



	Rel error	SBN 1604-5	Estimate	Adjusted	Result	Average													SVD variables	w-diagonal	residual
Outer dia 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
no 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
Dyn load	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
Stat load	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 out dia	0.02	36.00	36.82	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 dia	0.02	59.00	58.04	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
flange w	0.16	11.00	9.28	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 [kgm2/mm]	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																					

SVD Analysis

- SVD validation
  - The “BNFN 10020A-7.5” ball screw that was excluded from the analysis
  - Optimization with the built-in solver in Excel:
    - Minimize relative error by changing the SVD variables

Constraints on SVD variables to only vary between -2 and 2 (To allow light extrapolation)

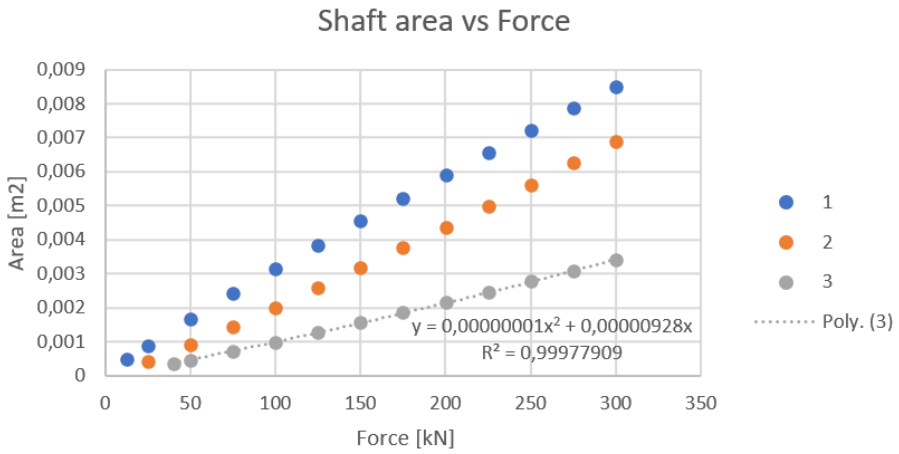
	Rel error	BNFN 10020A-7.5	Estimate	Adjusted	Result	Average														SVD variables	w-diagonal	residual
Outer diameter shaft	0.04	100.00	104.05	2.02	0.34	1.68	0.177	-0.027	0.002	-0.019	0.011	-0.002	0.005	-0.002	0.007	-0.003	-0.001	0.005	0.002	2.00	9.11	75.14
Lead	0.01	20.00	19.88	1.30	0.26	1.04	0.143	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																					

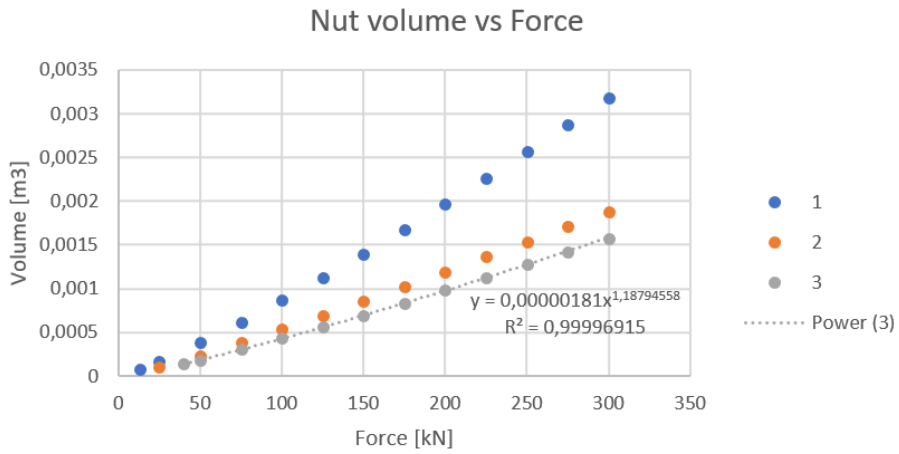
SVD Analysis

- SVD Estimation using the built-in solver
  - To estimate the characteristics of new ball screw designs with the three SVD-variables from different requirements
- Optimization set-up
  - Objective:
    - Minimize lead
  - Design parameters:
    - The three SVD variables
    - Static-load rating: 0 – 300 kN
  - Constraints:
    - SVD variables can only vary between -2 and 2
    - Static-load rating and number of circuits

Results

- The process described in the previous slide was then repeated with the different input constraints to give several ball screw design estimates
- Some obtained relationships between characteristics:





Final Ball Screw Estimation Model

- The previous results were combined into a final estimation model for ball screws using trendline fitting
- Based on static load rating

Shaft mass/meter estimation -> $m_{sm} = 0{,}0354 * F^{1{,}1589}\ [kg/m]$

Shaft area estimation -> $A_s = 0{,}00000001 * F^2 + 0{,}00000928 * F\ [m^2]$

Nut mass estimation -> $m_n = 0{,}0129 * F^{1{,}1804}\ [kg]$

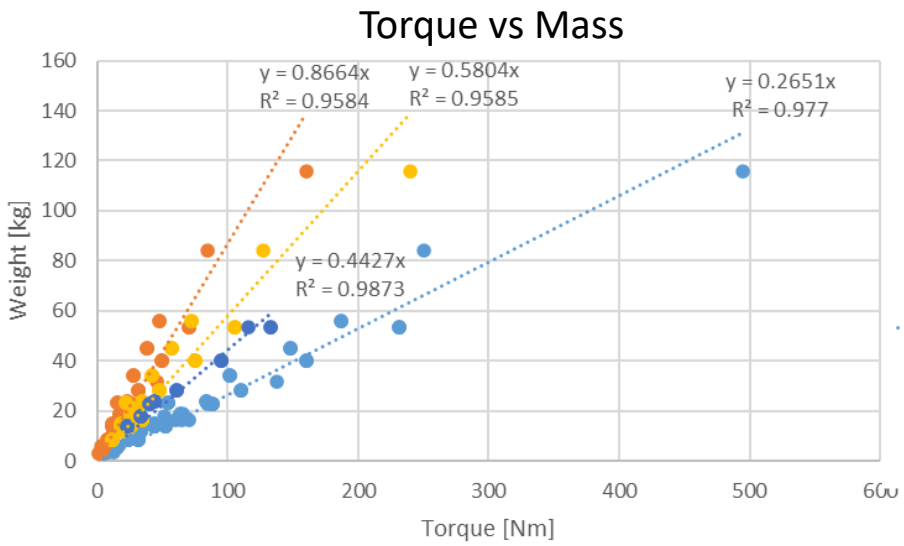
Nut length estimation -> $l_n = 0{,}0259 * F^{0{,}3824}\ [m]$

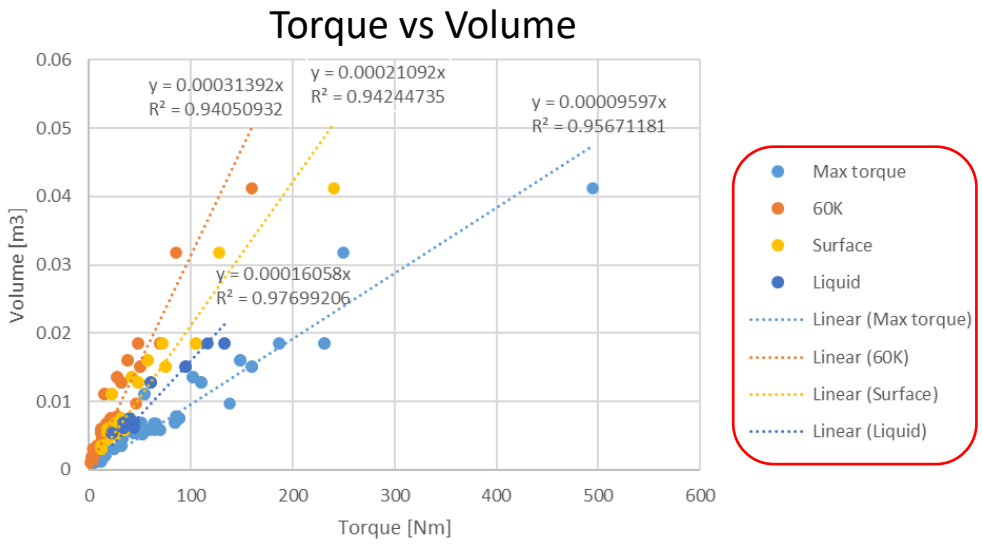
Nut volume estimation -> $V_n = 0{,}00000181 * F^{1{,}18794558}\ [m^3]$

Lead estimation -> $L = 1{,}0227 * \mathrm{F}^{0{,}3676}\ [mm/rev]$

Electric Motor Estimation

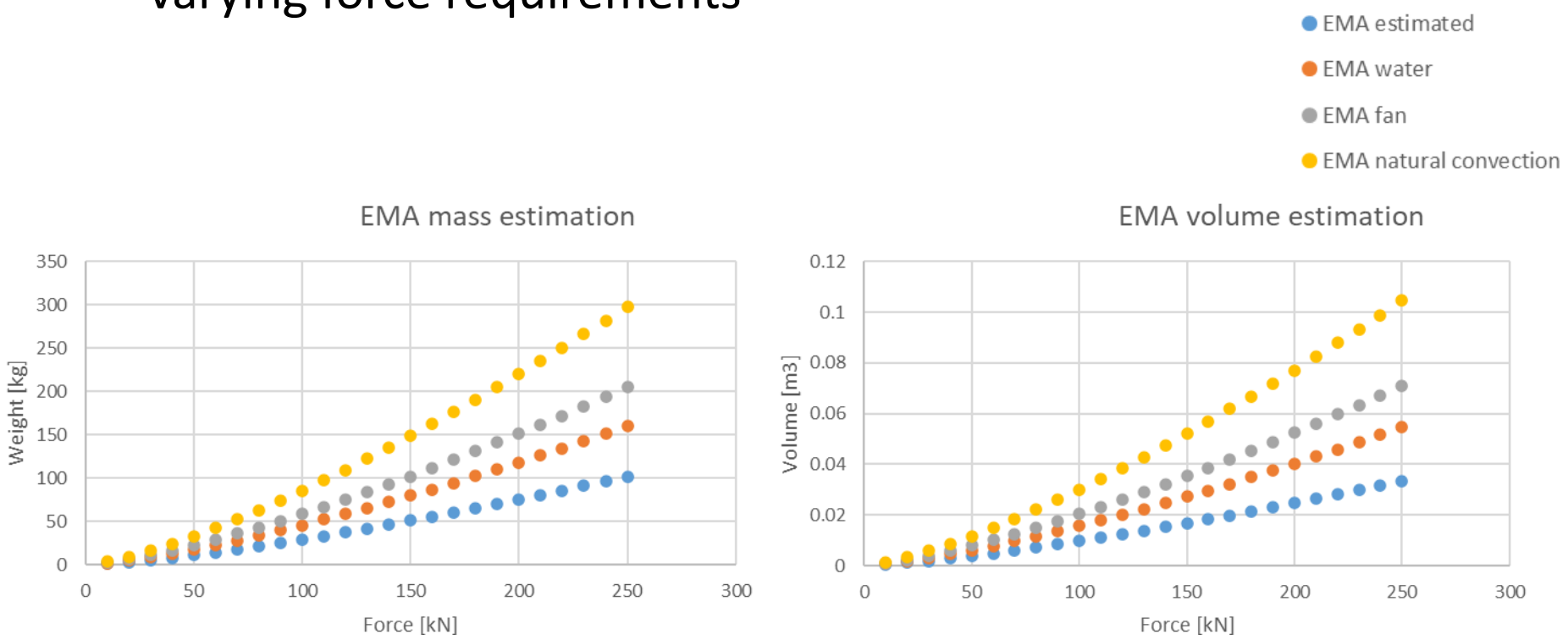
- Electric motor data from Bosch Rexroth
  - Permanent Magnet Synchronous Motor (PMSM)
    - High-power density, efficiency and reponse
- Regression analyses to derive how weight and volume varies with output torque
  - Four output torque levels





Electro Mechanical Actuator (EMA) Estimator

- Ball screw and electric motor estimators combined
- The total mass and volume of an EMA with a single ball screw and PMSM can thereby be estimated based on varying force requirements



Conclusions

- This work has shown how an estimator for aircraft actuator characteristics can be created with statistics and different regression analyses
- Singular Value Decomposition (SVD) is a convenient way of indetifying principal components and to estimate characteristics from limited information

Future Work

- More and different validation data
- Automatization of the work
- Expanded data set with more parameters
- Compare the weight of existing actuator architectures with the obtained estimates to possibly “fine-tune” the estimations

WIEFP 2022

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Thank you for listening!

AN ESTIMATOR FOR AIRCRAFT ACTUATOR CHARACTERISTICS USING SINGULAR VALUE DECOMPOSITION

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