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LUT School of Energy Systems
LUT Mechanical Engineering

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INTEGRATION OF POSITION SENSOR WITH ACTUATOR AND USING DFMA IN THE DESIGN OF AN ACTIVE MAGNETIC BEARING

Updated 06.09.2021

Examiner(s): Professor Jussi Sopanen
D. Sc. (Tech.) Charles Nutakor

ABSTRACT

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Master's thesis

2021

82 pages, 23 figures, 16 tables, and 2 appendices

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Keywords: DFMA, active magnetic bearing, integration, reverse engineering.

Active magnetic bearings (AMBs) have the potential to be incorporated into various high-speed applications. Owing to the benefits offered such as lubrication-free operation, energy efficiency, reliability, etc. Currently, an AMB is designed with a focus on performance. Little attention to ease of assembly and manufacturability is given in the design phase. The initiation for this research was laid out to assess the feasibility of applying design for manufacturing and assembly (DFMA) aspects to the design of an AMB.

DFMA would provide improved product in terms of modularity, cost-effectiveness, lower time to market, etc. Possible integration solutions for combining the sensor and actuator of an AMB were also reviewed. This research was conducted using a combination of interviews with firms, literature review, and analysis. New concepts were proposed based on results gained from DFMA analysis and design review carried out on an AMB developed at LUT. A selection matrix was used to find the best solutions. Top-rated conceptual solutions were analysed and the results were compared with those of the original assembly.

It was realised that the accuracy of the results and the amount of data available regarding assembly and manufacturing are directly proportional to each other. The proposed solutions outperform the present structure on the majority of criteria. Therefore, a product design such as AMB can be improved via DFMA. Also, methods using quantitative parameters in future shall provide improved product design with realistic numbers.

ACKNOWLEDGEMENTS

I want to thank my thesis examiner Professor Jussi Sopanen for great support and guidance during the work of my Master's thesis at LUT University in Finland. This Master's thesis was carried out in collaboration with LUT University and Spindrive. Special thanks go to D.Sc. (Tech) Nikita Uzhegov and D.Sc. (Tech.) Janne Heikkinen for providing me with this opportunity.

Without constant assistance from my thesis examiner D.Sc. (Tech.) Charles Nutakor, this thesis would not be possible. He always questioned my work, forcing me to think and develop. He provided me time and pointed me in the correct direction. He was patient with me and addressed all of my questions.

I would also like to thank D.Sc. (Tech.) Harri Eskelinen for taking an overview of the DFMA approach used and suggesting improvements to make the analyses complete. Finally, I'd want to express my gratitude towards my friends, girlfriend and family for their unwavering support during my education and thesis work. The past two years of study have not been easy, and COVID-19 has not helped in any matters. People close to me acted as a source of positivity and motivation.

Thank you very much!

Aditya Uday Kumthekar

Aditya Uday Kumthekar

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LIST OF SYMBOLS

a	Coefficient of thermal expansion
℃	Degree Celsius
C_c	Shape complexity
C_f	Surface finish complexity
C_m	Material cost
C_{mp}	Material complexity
C_s	Minimum section complexity
C_t	Tolerance complexity
d	Total deformation
dt	Temperature difference
€	Euros
F_m	Electromagnetic force
g	Gram
k_s	Current Stiffness
kWh	Energy in kilowatt-Hour
L	Circumference of cylinder
M_c	Manufacturing cost
M_{ci}	Manufacturing cost index
mm	Millimetre
P_c	Primary Processing cost
R_c	Relative cost
W_c	Waste factor

LIST OF ABBREVIATIONS

AIS	Artificial immune systems
AMB	Active magnetic bearing
BPF	Band-pass filters
CRAMB	Combined radial-axial magnetic bearing
DCM	Direct current measurement
DE	Design efficiency
DFA	Design for assembly
DFM	Design for manufacturing
DFMA	Design for manufacturing and assembly
DIN	German Institute of standardization
DOF	Degrees of freedom
EN	European standard
FEA	Finite element analysis
FEM	Finite element modelling
GA	Genetic algorithm
ISO	International organization for standardization
LPF	Low-pass filters
OEM	Original equipment manufacturer
PCB	Power amplifier
PEEC	Printed circuit board
PWM	Pulse width modulation
SME	Small-medium enterprises
UML	Unified modelling language
YBCO	Yttrium barium copper oxide

1 INTRODUCTION

To realize the designed product with a higher degree of efficiency in terms of production time, serviceability, reliability, etc. it is essential that manufacturing and assembly are considered starting from the preliminary design stage. Design for manufacturing (DFM) emphasizes cost-effectiveness and easy manufacturability in the product design phase while Design for Assembly (DFA) refers to designing a product possessing attributes facilitating easy assembly. The merger of these two methods led to the creation of a methodology termed DFMA (Boothroyd 2002, p. 1). The Boothroyd-Dewhurst DFMA approach is the most extensively used since it gives precise findings depending on variables like prices, timeframes, and dimensions. The Lucas DFMA technique, on the other hand, considers the key aspects such as functionality, fit, handling, and manufacturing. (Boothroyd 2002, Pp. 11-15; Kamrani and Nasr 2010, p. 152.)

In an active magnetic bearing (AMB) the rotor is suspended by applying the required electromagnetic force of attraction by electromagnets of a stator, without any physical contact between stator and rotor. The gap sensor estimates the position of the rotor, microprocessor control unit compares it with the reference position and supplies corrective current to the electromagnets via amplifiers which then generate force, that keeps the rotor at the centre of the stator as seen in Figure 1. (Maslen and Schweitzer 2009, Pp. 1-3.)

In this thesis possibility and probable outcomes of DFMA implementation on a radial actuator of an AMB integrated with sensors will be studied. The state of the art provides adaptability to a wide range of rotational speeds reduced vibrations, the ability to work in a vacuum, and a high-temperature Environment, up to 550 degrees Celsius. AMB’s are used in high-speed machining spindles, centrifugal compressors, gearboxes, oil pumps, turbomachines, oil pumps, organic Rankine cycle generators, jet turbines, gas blowers, and turbines, etc. (Breńkacz et al. 2021, Pp. 1-31; Siva Srinivas et al. 2018, Pp.537-572; Spindrive 2021; Waukesha Bearings 2021a.)

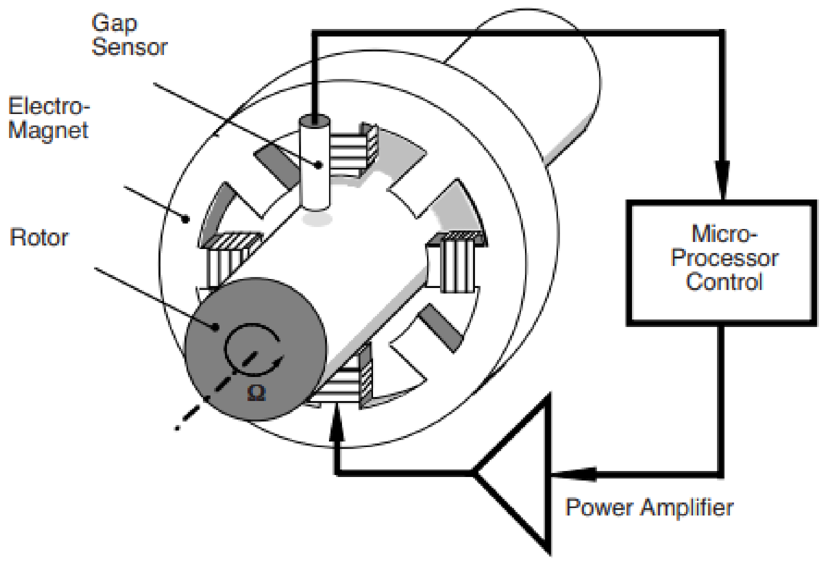


Figure 1. Operating principle of a radial AMB (Maslen and Schweitzer 2009, p. 2).

Literature and books containing information regarding the design and control of AMBs are available (Breńkacz et al. 2021, Pp. 1-31; Chou et al. 2016, Pp. 2395-2420; Hofer et al. 2009, Pp. 625–630; Maslen and Schweitzer, 2009; Raghunathan and Logashanmugam 2019, Pp. 3481-3492). Literature related to the design of AMB's with emphasis on easy assembly and manufacturing is rarely apparent (Naiju 2021, Pp.7473-7478).

Some methods to improve AMB and other mechatronic machines in terms of manufacturability and assembly present in literature are, using stator of a motor as an AMB stator, incorporation of standard industrial components, application of configuration design, and collaborative assembly (Chou et al. 2016, Pp. 2395-2420; Gualtieri 2021, Pp.2369-2384; Han et al. 2015, Pp.2284-2293; Huang and Fang 2016, Pp.2766-2774; Koehler et al. 2017, Pp. -1-3; Smirnov et al. 2017, Pp. 9876-9885; Tshizubu and Santisteban 2020, Pp. 1-9; Zheng et al. 2019, Pp.373-384).

Literature related to possible sensors and actuator integration solutions attempted in past are reviewed (Pat. US10030702 B2 2018, Pp 1-6; Ernst et al. 2020, Pp.39-43; Jiang et al. 2019, Pp. 5460-5469; Koehler et al. 2017, Pp. 1-3; Müsing et al. 2021, Pp. 1- 5; Niemann et al. 2013, Pp.12149-12165; Park et al. 2008, Pp. 1757-1764; Raghunathan and Logashanmugam 2019, Pp. 3481-3492; Sun and Zhang 2014, Pp. 1950-1960; van Schoor et al. 2013, Pp.441-450; Zhang Gang et al. 2011, Pp.373-384).

This section is split into the mechanical, sensor less and hybrid types of integration. This thesis would be useful for readers to gain an idea of all possible integration solutions.AMB is still not an off-the-shelf product. It will be made on an order as per requirements to provide the best performance. A radial active magnetic bearing is studied to understand if the proposed methodology can provide improvements and to what extent. Lucas method is applied to conduct DFMA analysis as it focuses more on functionality and demands less data. Analysis and design review of the assembly provides numerous conceptual designs with changes to the original assembly. A selection matrix based on the methodology proposed by Pugh is used to select the productization scheme, as it needs the least number of comprehensive details, it is helpful in conceptual design selection and decision making (Butt and Jedi 2020, Pp. 2-56).

Various qualitative factors assessing the modularity, ease of assembly, and manufacturing are set as criteria. Top-rated solutions are analysed and results of the same are compared with those of the original assembly. There are some things to be considered before adopting a shrink-fitting solution, even if it scores well in all criteria, such as high initial investment, lower flexibility to design changes, thermal changes, etc. But if the product is of a high-volume nature and tests prove the feasibility, this is the most cost-efficient and best solution in long run. The DFMA analysis must be conducted with an open mind, which means not just following the regulations but also thinking outside the box. Without lowering the number of components, it is feasible to simplify production and assembly.

In the instance of the clamp solution, we can see that it has a lot of modularity. It may be used even after when design changes demand the dimensions of deviate. The Lucas method followed gave factors related to only non-advanced methods. For current times and mechatronic assemblies where advanced methods like laser processing, additive manufacturing, etc. are used, parts such as coils, wires are not suitable for the current DFMA analysis method.

Revamp of this method is necessary so that it could be applied to products of present and future age as it can make assembly and manufacturing easy. Also, personnel performing analysis shall know about materials, electronics, mechanics, etc. In the future methods based on quantitative data shall be used as they would provide a better product with realistic metrics, providing the user confidence in whether the solution is viable or not.

1.1 Research questions

Based on the direction in which load is to be sustained by the bearing, concerning the rotor axis, an AMB can be classified in two varieties namely, radial magnetic bearing and axial magnetic bearing. Major components of a radial AMB are actuator, controlling unit, and position sensors. A typical radial magnetic actuator is a stator with windings. While the position sensors are available in various forms and work on different principles. Integration of these two components shall provide various benefits. One of them focuses on integrating parts to make assembly and manufacturing faster. To assess the feasibility of DFMA application and integration to obtain an improved AMB, this thesis focuses on finding the answers to the questions mentioned below:

1. Feasible methodologies for productising sensors and actuators into a single unit?
2. How can DFMA be applied to the above-mentioned product?

1.2 Aim and objectives

To review various possibilities of combining the actuator and sensor of a radial active magnetic bearing into a single unit. Also, conduct DFMA analysis on an active magnetic bearing design to achieve an improved product design with attributes such as modularity, easy assembly and manufacturability.

1.3 Scope

The design of the 3D model of AMB was reviewed using various modules present in SolidWorks. Only radial AMB was considered for the case study. A hybrid method for DFM analysis is employed where a combination of qualitative and quantitative parameters are used. No experiments were performed during this research. The study was performed with available and derived data for example mass, the number of manufacturing stages required, etc. Information regarding assembly times, manufacturing costs, etc. were not available which are typically available during a DFMA analysis. The selected method for DFMA analysis was modified to make it more favourable for the product under consideration. The effects on the product family due to changes in design gained from the DFMA application are not considered.

2 DFMA AND INTEGRATION OF AMB COMPONENTS

The breakdown of the content in this section is as follows: The background of DFMA is described with its principles and basic steps of performing analysis. In section 2.1.1. outcomes of DFMA analysis on numerous products from various areas via different approaches are presented. Section 2.2 describes the different types of structures of an AMB, the current state of the art and previous studies of optimization carried out on AMBs and other mechatronic assemblies. The following section presents possible sensors and actuator integration solutions attempted in the past. These solutions were segregated in terms of the means of integration. For example, solutions, where integration will be achieved majorly via mechanical changes, are listed and described under the mechanical integration subsection. Similarly, solutions, where self-sensing technology and hybrid methods are applied to achieve integration, are placed under sensorless technology for integration and hybrid integration solutions respectively. The methodology of DFMA analysis and selection strategy is described in sections 2.4 and 2.5 respectively.

2.1 Design for Manufacturing and Assembly

DFMA has been around in Mechanical and Production Engineering in both industries and academics since the end of the 20th century. (Boothroyd 2002, Pp. 1-3). According to Scopus, the scientific research documents related to DFMA can be found dating from the year 1991. According to the data acquired from Scopus, it can be inferred that there has been a rise and fall in the number of research documents related to DFMA, but the overall trend seems positive. This may be because information regarding internal projects undertaken, and studies conducted by the industries are not made public. (Scopus 2021a.)

DFA refers to product design that focuses on making a product and its entire assembly as simple as possible. When compared to other costs involved in production, assembly activities are frequently the most costly in a production sequence.They are potentially the most lucrative to simplify. An assembly before and after applying DFA guidelines can be seen in Figure 2 below. The number of parts, joining methods, and assembly directions are reduced, leading to decreased assembly times. While DFM focuses on optimizing product configuration from a production standpoint by emphasising two major design aspects mentioned below:

1. Selecting the right manufacturing process chain for each component
2. Reforming the geometry of part design for that process chain.

Over 70 % of costs related to manufacturing are realised in the design stage. This helps in the quantification of manufacturing and assembly costs early in the development process to improve assembly efficiency, save money, and compare designs to competitors. (Naiju 2021, Pp.7473-7478.)

The term DFMA was introduced by Boothroyd-Dewhurst, whereas in the book, the author and literature gathered by him consider DFM itself covers the aspects related to assembly along with manufacturing (Bralla 1996, p. 28.)

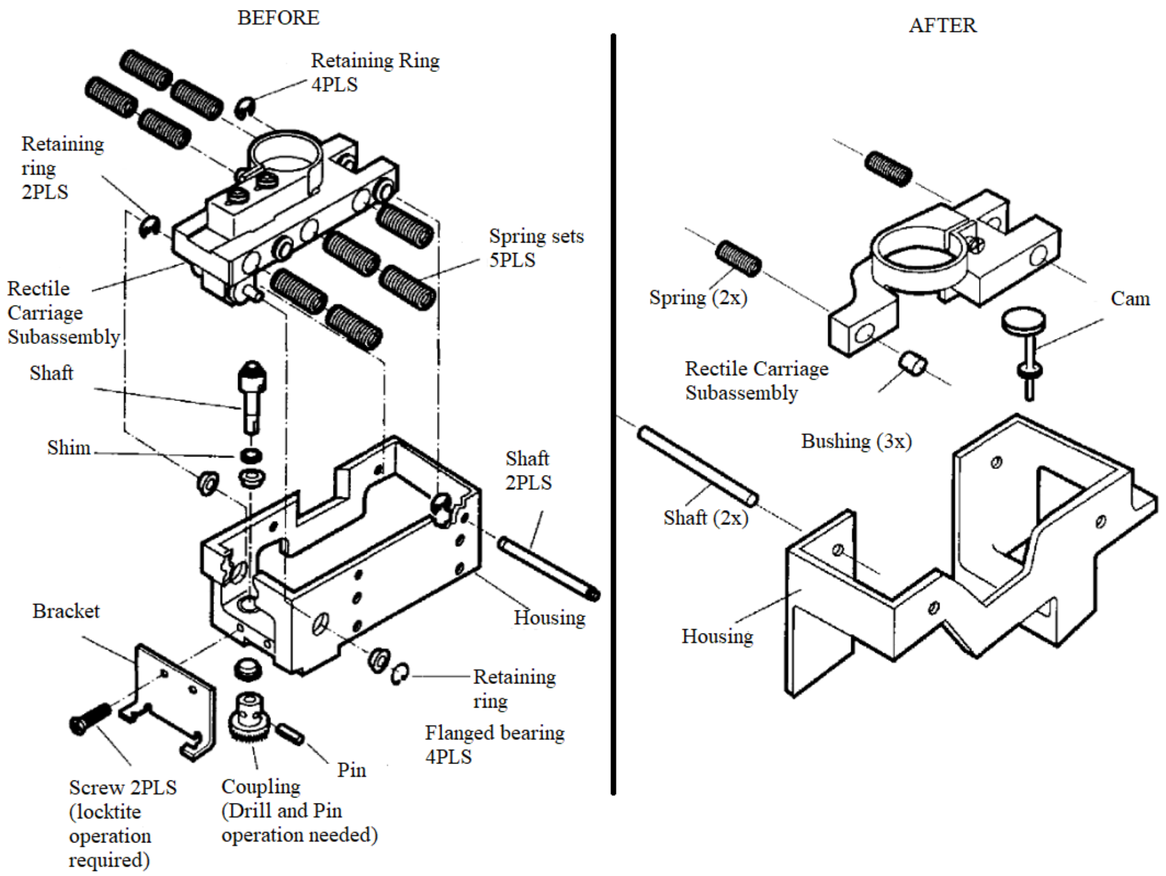


Figure 2. (a) assembly before and (b) after applying DFA guidelines (Boothroyd 2002, Pp 22-26).

Whitney used interchangeable components in the manufacture of muskets for the United States government. The American businessman Henry Ford broke down hand assembly into tiny pieces of repeated labor that could be done quickly. Ford characterized the successful model T automobile in his autobiography "My Life and Work" as having "simplicity of operation, perfect reliability, and excellent quality in materials utilized in that model." Ford's concept is now known as DFM (Design for Manufacturing). (Bralla 1996, Pp. 10-12.)

In the late 1940s, General Electric utilized value analysis methodologies. With the same, it was possible to determine the cost of a product as well as create other options for acquiring the product at the lowest possible cost. Value analysis is a philosophical method that involves evaluating and comparing the value and cost of each feature and aspect of a product design. The book "Metal Engineering Processes," is one of the handbooks published by the American Society of Mechanical Engineers (ASME) in 1941. The same offers designers a set of principles for improving the manufacturability of metal components produced using a variety of conventional manufacturing techniques. Despite the fact that author of this book did not use the term DFM, he was the first to organize DFM technique. (Bralla 1996, Pp. 12-14.)

Another popular but sparingly used approach for DFMA analysis is the Lucas method. This method can be distinguished from the Boothroyd-Dewhurst method as specific dimensions and costs are not considered. This approach consists of three distinct and sequential stages. The analysis is completed in three steps, each with its own set of findings that are reported in a chart for benchmarking. This method of evaluation considers the critical issues of assemblability and component manufacturing. For manufacturing-related matters, grouping technology is used to categorize components according to their interface features and material properties. It calculates an index, named manufacturing cost index that is used to assess the suitability of various manufacturing processes and operations. (Boothroyd Dewhurst, Inc. 2021.)

Geoffrey Boothroyd and Peter Dewhurst, developed the Boothroyd & Dewhurst DFMA system, to give designers a method for quantifying prototype designs to make automated assembly easier. This method was supplemented to include manual assembly for manufacturing engineers to justify automation proposals. The two improvement aspects aimed were reducing the number of parts and making the assembly operations easier. Producibility rules of that time, demanded designers to work on simplifying individual parts making them easy to produce and less expensive. However, a study conducted by Peter Dewhurst and his team revealed, fewer and multi-functional components reduced production costs. In 1980 Dr. Peter Dewhurst collaborated with Doctor. Boothroyd on the Apple II Plus program kit named Design for Automatic and Manual Assembly. After this other digital firms approached and Boothroyd Dewhurst Inc. in 1983 was established. Several large businesses, including Ford and General Motors, reported saving billions of pounds owing to the DFA initiative. In 1985 further research was conducted to add the DFM module to the existing one. (Boothroyd Dewhurst, Inc. 2021.)

Some DFMA principles considered during analysis are as follows:

1. The ability to delete components or merge with the assembly
2. Reduced average time required to grip, manoeuvre, and insert the part
3. Avoiding reorientation during manufacturing and assembly
4. Plan for ease of assembling
5. Design parts for easy service, handling, and insertion
6. Mistake-proof product design and assembly, etc.
7. Improving the ergonomic conditions for the worker
8. Well-designed manual assembly design might lead to an automated assembly procedure.

The general process of applying DFMA with some modifications to the original flow chart for improved clarity can be seen in Figure 3 below, which starts with DFA analysis of the conceptual design to reduce assembly time by simplifying, integrating, and making the components modular. Then, based on early cost estimates, the most profitable materials and processes are recognised. The original design and alternate solutions are assessed. Finally, trade-offs are made to obtain the best solution. Thorough analysis for DFM is conducted for reduced manufacturing costs before prototype testing followed by production (Boothroyd 2002, p. 15.)

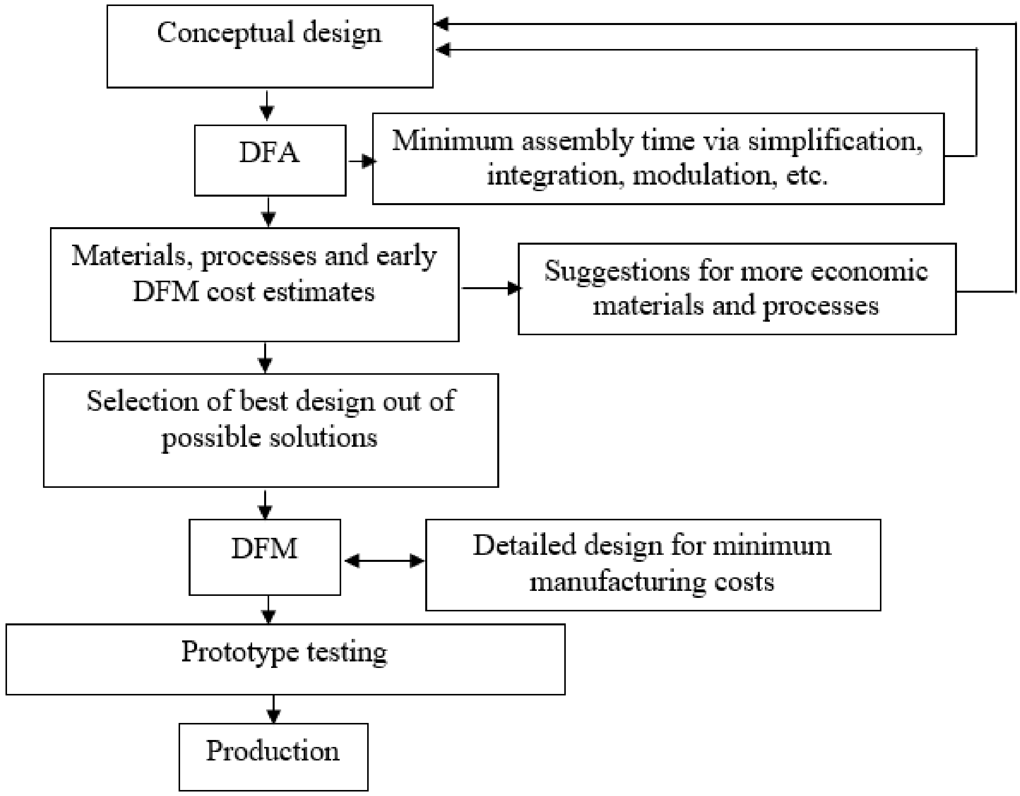


Figure 3. DFMA application process (Boothroyd 2002, p. 15).

The author has reviewed current expertise and state-of-the-art regarding DFMA with the help of product case studies conducted in various fields such as industrial, electrical, automotive, aerospace, consumer good and other Engineering applications. To excel in this competitive market, manufacturers are aiming for an improved product in terms of cost efficiency and manufacturing speed. While various DFMA methods and tools are available, it remains unclear which of them should be applied for a particular product to gain valid results. The author states to attain the maximum potential of DFMA, the questionnaire used to examine the product must be easily interpretable and the capacity of the company must match the goals that have been set. Case studies of different products which incorporated the DFMA approach for product development are mentioned in Table 1 below. Electric motor production time and overall product cost were reduced by 50% and 45 % respectively. Along, reduced program timing, reductions in assembly times, and defects were observed with door locks of MTZ tractors after DFMA application. Another sub-assembly applied with process modelling and activity-based costing provided variation in product cost for different designs built, based on questionnaire and a personal interview. This assisted designers to gain the most optimal subassembly design. DFA and conceptual DFA approach aided designers in the redesign of the CNC machine tool holder carousel to obtain cost-effective assembly. The materials and manufacturing processes of redesigned tool holder were also assessed. (Naiju 2021, Pp.7473-7478.)

Table 1 Case studies of different products and the DFMA approach used for development.

Area	Product	DFMA approach incorporated
Industrial	Electrical motor	Lean manufacturing and DFMA complimented each other to gain improved products.
	Building project	DFMA application through value Engineering.
	The door lock of MTZ tractors	Step by step DFMA approach helped identify costs in the early stages.
	Desk organiser	DFMA integrated with Design for Environment.
	CNC machine tool holder carousel	DFA and conceptual DFA
	Food conveyor system	Boothroyd-Dewhurst DFMA software and Pugh’s selection matrix
Electrical	Radiator	The implementation of DFMA in design practice is explored and documented to coordinate the relationship between product styling effect and structure.
	Motor junction box	DFMA led to new construction with grounding connected 360 degrees around the cable.
	Fuel cell system	DFMA stye cost estimation
Aerospace	Aerospace craft component	DFM and DFA analyses were conducted separately.
	Aircraft design	Application of DFMA principles

Table 1 continues. Case studies of different products and the DFMA approach used for development.

Area	Product	DFMA approach incorporated
Automotive and defence	Future combat system missile	DFMA workshops
	Body panels	DFM rules for cost reduction
	Car driver seat	DFA analysis, DFMA principles, and Poka-yoke.
Other applications	Various consumer goods were studied.	DFMA software and tools • DFMA tests • Error proofing • Boothroyd and Dewhurst method • DFMA principles
	Water nozzle	DFMA-Lucas method Temset software.

For industrial electrical products such as radiator was improved with reduced parts while other products such as motor junction box and fuel cell system, were made cost-effective via structural and material changes, respectively. The approach incorporated criteria such as enterprise’s expectations, manufacturing technologies, market developing status, and restraining factors in the case of the radiator. Aerospace craft part and aircraft design subjected to DFA and DFM analysis led to improvements with some discrepancies. It was inferred that an integrated DFMA tool might assist in obtaining better results. DFMA workshops consisting of members from different disciplines was proposed to be a regular practice after improvements gained for future combat system missile. Two sub-assemblies of Bell helicopters were applied with DFMA, which lead to parts integration and elimination of few manufacturing stages resulting in weight and cost reduction. Various assemblies in automobiles from different manufacturing brands have benefited from DFMA tools and software. Some innovative techniques such as self-threading screws, avoidance of flimsy parts, and use of captured washers were imposed on water flow valves via DFMA. (Naiju 2021, Pp.7473-7478.)

DFMA-Lucas hull methodology was used to improve water nozzle design, the product was analysed with TeamSET-Lucas Hull base software. Due to fewer parts, the redesigned product has better attributes such as low manufacturing costs and assembly time. (Ahmad et al. 2018, Pp. 12-23.)

A case study where, an industrial food conveyor system is redesigned and tested for structural performance using Finite Element Analysis, based on improvements gained from analysis, performed using DFMA software is presented in this paper. Components that were either not properly designed or were over-designed and had cost repercussions in conveyor production were removed. The best solution was chosen using the Pugh controlled convergence procedure. The time and cost required to assemble the new conveyor system, the weight of the conveyor, and overall manufacturing cost were reduced by 57%, 25%, and 29% respectively. (Butt and Jedi 2020, Pp. 2-56.)

The car driver's seat was analysed along with the manufacturing processes used. Various improvement possibilities were explored and changes to the design were made accordingly. DFMA methodology application assisted in optimization by complicating the components of the product, which reduced the number of parts, also the same performed identically and somewhat better in the crash test compared to the original design. (Medvecký et al. 2020, Pp. 3-12.)

2.2 Active magnetic bearing

Traces of electromagnetic suspension have been found in scientific experiments related to physics and particle science. Samuel Earnshaw in 1842 stated that levitating magnetic elements using any arrangement of magnets and gravity stably was not possible. The law was further studied and a patent for hovering suspension was filed by Kemper in 1937 in the hope to realize advanced transportation. Werner Braunbek extended his contribution to the theorem in 1939 stating diamagnetic materials are the only way to achieve purely permanent magnetic stability of an object. During the Manhattan Project in the 1940s, Jesse Beams used active magnetic bearings to develop uranium centrifuges. A patent application for "Suspension of Rotatable Bodies" was submitted. S2M, a corporation, developed the first spinning magnetic bearings in 1976. (Maslen and Schweitzer 2009, Pp 5-10.)

Although it has been observed that magnetic bearing was studied since the beginning of the 20^{th} century, research articles mentioning the terminology AMB can be found since 1975 as seen from the Scopus analysis (Scopus 2021b). Active magnetic bearings (AMBs) have been studied and used in high-speed machines as a replacement for conventional roller bearings as they provide numerous benefits (Breńkacz et al. 2021, Pp. 1-31). Energy loss associated with electric machines installed with conventional bearings is significant and depends on the type of application (Nutakor et al. 2018, Pp. 34-45).

Along with energy losses the conventional bearings demand lubrication and maintenance as there exists a physical contact between rolling element bearing, with varying asperity contact condition and hence friction coefficient which depends on the lubrication regime, a factor that contributes to the wear rate at the contact surfaces (Nutakor et al. 2019, Pp.509-522). Load bearing capacity depends on the structure of electromagnets (stator), material properties, electronics, and control system incorporated. System parameters such as current stiffness k_i and displacement stiffness k_s determine electromagnet's force of attraction F_m and the same are dependent on distance between rotor and poles. (Breńkacz et al. 2021, Pp. 1-31.)

2.2.1 Structure of radial actuators.

Two major types based on magnetic polarity experienced by the rotor are heteropolar and homopolar radial actuators. In other words, the travel of magnetic flux loop between rotor and stator determines the type of radial bearing in consideration as seen in Figure 4 below. Selection is solely dependent on the application as both present advantages and disadvantages with respect to specific areas. The homopolar structure is more suitable for axial loads and vacuum applications as it experiences low rotational losses. This structure has also proved its compatibility with high-power equipment such as aircraft turbines. (Breńkacz et al. 2021, Pp. 1-31.)

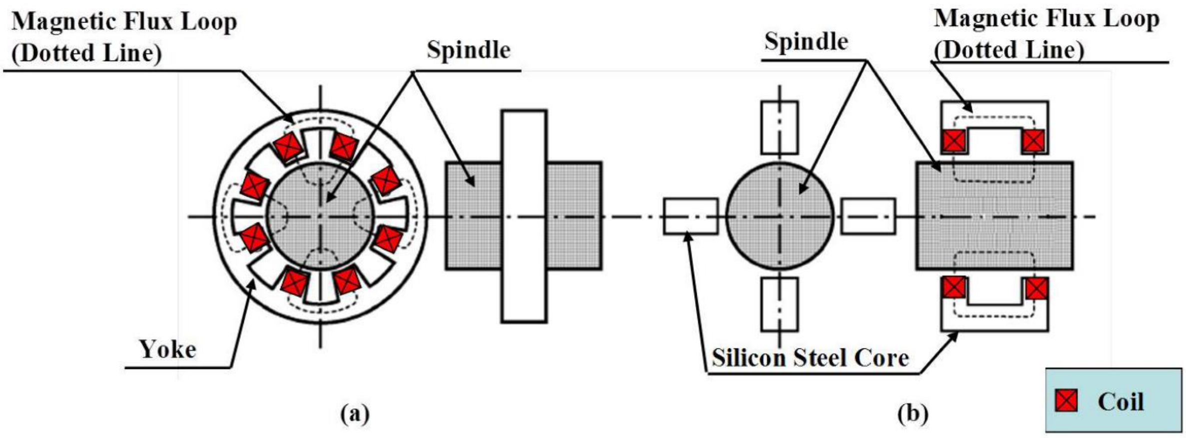


Figure 4. Major types of configurations of an AMB: (a) Heteropolar design, and (b) Homopolar design (Lee and Chen 2016, p. 2).

Permanent magnetic biased homopolar structure as shown in Figure 5, provides benefits such as smaller overall radial diameter, lower force-displacement factor k_s and less variation in rotor position. High cost is a drawback of this structure but is sometimes mitigated due to lower power consumption. (Maslen and Schweitzer 2009, p. 83). On the other hand, heteropolar is easy and costs less to manufacture (Smirnov et al. 2017, Pp. 9876-9885.)

Homopolar radial bearing with permanent magnet biasing is presented in this master's thesis. In the case of time-varying loads insulation between laminated layers blocks Eddy currents induced by alternating flux. Control flux will partially travel perpendicularly through the lamination plane. Eddy currents are induced which counter the original control field reducing the load capacity. This issue can be mitigated by adding a permanent magnet right next to the laminated stator core which generates bias flux. A methodology to design a bearing and optimisation is described. (Nurminen 2020, Pp. 5-62.)

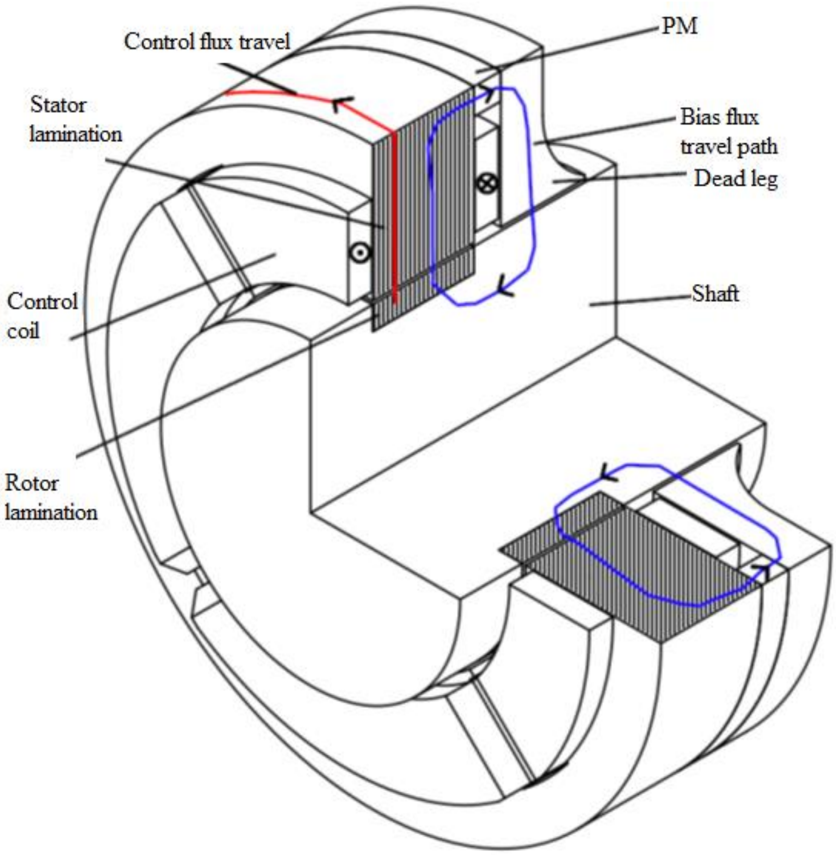


Figure 5. Schematic diagram of homopolar structure with permanent magnetic biased (Nurminen 2020, p. 13).

2.2.2 The state of the art

To get the best performance from a mechatronic machine such as AMB, cooperation between teams belonging to multiple disciplines and stakeholders is essential. End users, designers, and manufacturers must closely collaborate to gain an optimized product. Off-the-shelf AMB solutions with a high scope of integration owing to the use of standard models are provided by giants like SKF, Siemens, and others. (Siemens Global 2021; SKF 2021.)

Other companies majorly indulged in activities complimenting original equipment manufacturers (OEM's) are Spindrive, Waukesha, and Calnetix. These provide solutions for applications such as turbo compressors, blowers, organic Rankine cycle generators, gas turbines, pumps, expanders, etc. (Calnetix Technologies 2021; Spindrive 2021; Waukesha Bearings 2021a.) Along with the above-mentioned applications AMB has also successfully proved its efficiency in fields such as medical and material science via blood pumps and separators (centrifuges). The capacity to function in a vacuum, at high speeds, at extremely low and extremely high temperatures, and in an acidic or alkaline environment are the major benefits of active magnetic bearings. can all be utilized with active magnetic bearings can be used for sensing and vibration excitation. As a result, AMBs open up new opportunities in turbomachinery, such as enhanced detection, diagnosis, and optimization approaches. (Breńkacz et al. 2021, Pp. 1-31.)

AMBs incorporated in flexible rotodynamic systems were thoroughly reviewed with a significant emphasis on condition monitoring and vibration suppression. Various techniques used for condition monitoring, vibration suppression, and stability improvement are described along with comments. Applications where AMBs and other types of bearings are used independently and in conjunction are mentioned briefly. (Siva Srinivas et al. 2018, Pp.537-572.) AMBs and the same combined with other bearing technologies seem to be proving a worthy solution for flexible rotor dynamic system applications.

Currently, AMBs are employed in machines where speeds range from a few hundred to 300,000 rpm. Demerits include high initial price, lower damping when compared to hydrostatic bearings, require more space than traditional bearings, continuous power supply requirement, complex design and risk of attracting metallic scrap generated in machine tool applications. (Breńkacz et al. 2021, Pp. 1-31.) Ren et al. documented the design and optimization approach for an advanced version of AMB which employs High-temperature superconductor (HTS) material. This arrangement generates perfect magnetic conditions leading to the self-stabilized suspension. Better stiffness and load-bearing capacities are key reasons to opt for this type of bearing. (Ren et al. 2019, Pp.1-5.) Also, the same is easy to manufacture and provides a more compact design (Kurbatova et al. 2020, Pp. 1-9).

2.2.3 Optimization/DFMA of AMB and other mechatronic machines:

Single objective Optimization of AMB is treated as a constrained optimization problem. Three Artificial immune systems (AIS) approaches namely, clonal selection-based AIS (CLONALG), Genetic algorithm (GA), and AIS for constrained optimization (ARISCO) are applied to a radial AMB. ARISCO performed better than the other two when overall performance is considered. (Chou et al. 2016, Pp. 2395-2420.)

Multiple objectives optimization is applied to the Combined radial-axial magnetic bearing (CRAMB) of a compressor for increased critical speed of the rotor. PM ring is used to generate bias flux. Bearing stator outer diameter is determined based on the outer diameter of motor stator and manufacturing of motor shell. Finite element modelling (FEM) analysis resulted in improved maximum magnetic forces, reduced eddy current losses, and axial length. A prototype was manufactured to verify the results. Experiments included current-stiffness and displacement-stiffness tests. The maximum error between test results and FEM results mainly owing to material related and FE modelling was 6.93%. This method after better modelling and accurate inputs can provide an optimized product. (Han et al. 2015, Pp.2284-2293.)

A similar GA approach is applied to electrical a machine. Force specification, nominal speed of the rotor, maximum flux density are decided based on a linear region of material BH curve, air gap and coil current density along with iron ratio determine the final geometry of an AMB and same are set appropriately. Axial bearing dimensions and properties had a slight impact on machine parameters. To check the accuracy of the optimization procedure and analytical results, FEM simulations were performed and a difference of 15% was observed. A prototype is built to verify the proposed method experimentally. The difference between test results and design estimations was well within acceptable limits. Therefore, this method allows optimisation of a high-speed machine including the AMB,s. (Smirnov et al. 2017, Pp. 9876-9885.)

A permanent magnet electric machine is designed and optimised with constraints such as mechanical strength, rotor dynamics, mechanical losses, and the thermal field. External water-cooled jackets and pressurised air flow are provided to remove the heat from the stator of radial AMB and airgap, respectively. (Huang and Fang 2016, Pp.2766-2774.) It can be observed that AMBs are designed along or for specific applications to gain an optimised and best-performing system. Mechatronic machine design involves multidisciplinary integration. Also, the design of the same must cover manufacturing aspects to obtain a product that is optimised in terms of costs and performance. As mentioned above to get the best performance AMBs must be designed for the target application in close coordination with stakeholders. That leads to the design and use of components. If we talk about AMB and other mechatronic machines, some attempts to achieve cost-effectiveness, easy manufacturing, and assembly by changes in design are as follows: emphasis on the merits of coupling standard industrial components in AMB can be observed in this research study. Industrial components are designed with robustness, modularity, reliability, international standardisation, operation cost-effectiveness. The same is produced in higher quantities which creates scope for analysis and proper implementation of quality control which assists in product development and reduction in failure rates.

Koehler et al. state that the price of mechanical parts is not high as compared to other parts of the system. Therefore, not much study is conducted to check if they can be replaced with standard alternatives. Also, the stator of the bearing resembles the stator of an electric motor, the same tools and processes can be used for manufacturing AMB stator. (Koehler et al. 2017, Pp. 2-3.) As the same processes are used to manufacture stators. From this, one can infer that it is possible that optimization techniques and methods developed for motor stators can be applied to AMB stators to achieve easy assembly and manufacturing.

Configuration design lets the designer select the most suitable combination from a pool of different customizable options to gain desired product. Implementation of configuration design for mechatronic machine design leads to numerous alternatives, owing to its multidisciplinary and complex nature. A unique configuration design technique to solve this issue and achieve simultaneous interdisciplinary integration with an emphasis on industrial production and processes is suggested. An interface model facilitating the configuration design with a common representation of interfaces between alternatives is described. The unified modelling language (UML) was used in the model interface, where information regarding relationships among objects is evaluated based on set rules. The elimination step proposed a reduced number of incompatible combinations for a robotised welding system under study and allowed designers from different disciplines to select the best set from a list of alternatives. (Zheng et al. 2019, Pp.373-384.)

Electric rotary machines consist of windings that generate the required electromagnetic force. The stator of radial magnetic bearing is structurally identical with the stator of electric motor. Documents regarding the manufacturing of electric motors state that the general assembly of an electric motor stator is not fully robotised but there exists some human intervention through the manual assembly.

A systematic methodology for designing human-robot collaborative assembly is presented with a mechatronic machine as a case study. This approach improves worker health conditions and production performance. Attempts to propose a method that would easily be adaptable and applicable for small-medium enterprise (SME) with manual assembly stations where knowledge about the concerned technology seems limited were done. However, this methodology can also be applied to enhance the existing collaborative assembly system. Assembly tasks were divided among robot and operator based on suitability. Multiplication of manual time with coefficients and a digital simulation model was used to derive assembly task times. The method was clearly stated and a reduction in assembly time was evident for the touch screen cash machine. Results are gained in terms of monetary elements via cost and profit analysis by using the payback period (PBP) as a key performance indicator (KPI). Scheduling is based on a man-machine chart (MMC) which is an easily interpretable and commonly used tool in the industry, further favouring the applicability of this method. (Gualtieri 2021, Pp.2369-2384.)

High rotation speed demands of oil and gas industries are met with the provision of the latest bearing technologies from world-leading magnetic bearing manufacturers namely, SKF and Waukesha. AMBs for low-speed medical applications have also proved their feasibility. It was stated that the material required for the production of AMB is available in the market and the same being inexpensive as well. Although owing to customised manufacturing practices, the cost of manufacturing AMBs is high. This is because AMB must be designed closely according to the system they would be employed. To tackle this problem some researchers have attempted changing structure, winding alterations of AMBs, and conversion of induction motors into an AMB. Distributed winding generates higher forces as the same distributes higher magnetic flux along the air gap. (Tshizubu and Santisteban 2020, Pp. 1-9.)

Thizubu and Santisteban have further researched two-phase and three-phase stators, employed as AMB stators using linear modelling of the forces generated with the help of finite element analysis (FEA). The results were compared with a conventional 8 pole AMB stator. It was found that the direction of radial forces generated by proposed structures was not identical to that of 8 pole AMB, s. Hence, repositioning or reconfiguring of sensors is required. Finally, it was concluded that a three-phase stator in all windings supplied conditions has the potential to be employed as an AMB stator with proven merits such as low power loss, low sensitivity to rotor displacements, higher force generation and elimination of custom manufacturing. (Tshizubu and Santisteban 2020, Pp. 1-9.)

2.3 Productization

As mentioned earlier DFMA analysis will provide improvements for the considered components and assembly. With the help of the design review and the Lucas approach, we will gain possible solutions with changes or integration of components in the assembly of the case under study. Which will reduce the cost of assembly and manufacturing by making it easier. All kinds of mediums were used to look for possible solutions for integrating the sensor and actuator of a radial active magnetic bearing. These include research articles, Patents, books from databases, commercial and other websites, etc. So that for future similar projects this thesis would be useful to present an overall picture of possible integration solutions. The solutions are divided into subsections based on means of integration.

2.3.1 Mechanical integration

The arrangement of mechanical components in an AMB is described in Figure 6 below. It can be observed that a circular plate with provision to accommodate position sensor probes facing the rotor is attached to the AMB casing with the help of screws. The author suggests the stator of an AMB is quite identical to the stator of an electric motor. As mentioned earlier, It is conceivable to employ the same production standards, tools, and methods. (Koehler et al. 2017, Pp. 1-2.)

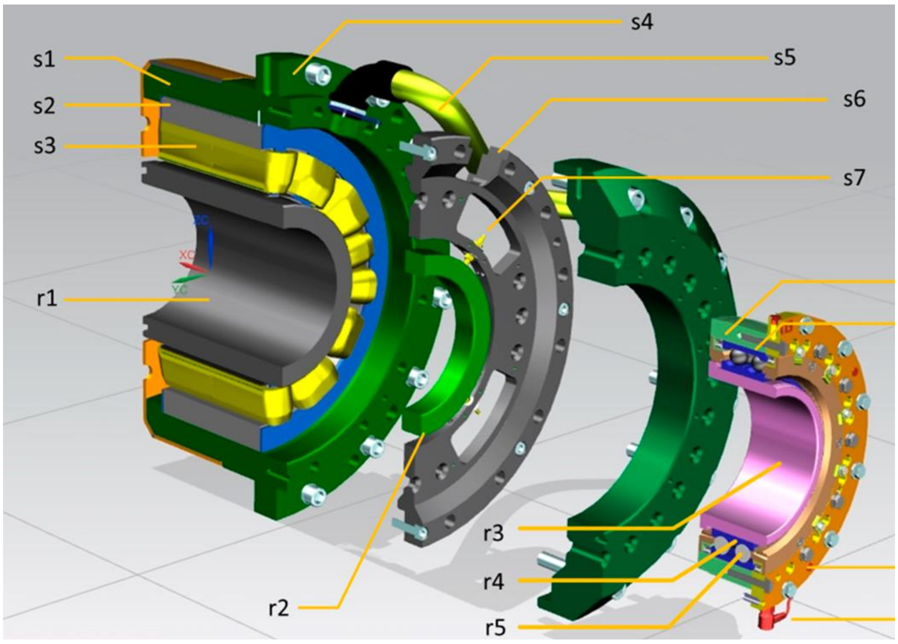


Figure 6. Exploded view of magnetic bearing components. s1: Casing, s2: laminated stator core, s3: stator winding, s4: bearing flange, s5: cable routing, s6: sensor placement assembly, s7: displacement sensor r1: laminated rotor core, r2: sensor target ring, r3: back-up bearing sleeve, r4: back-up bearing inner ring(s), r5: back-up bearing balls (Koehler et al. 2017, p. 2).

Eddy current sensors are commonly used since they have high resolution and wide bandwidth. To reduce the axial length of a high-speed machine. A permanent magnet biased heteropolar radial magnetic bearing integrated with sensor probes were presented in. (Sun and Zhang 2014, Pp. 1950-1960.) Other types include capacitive, inductive and magnetic (Waukesha Bearings 2021b).

Eddy current sensors are very easily influenced by the magnetic field. Hence, are usually placed outside the coils. A ring composed of 4 permanent magnets and sensor probes arranged alternatively so that each sensor falls in a different quadrant having a 90-degree radial difference along circumference is sandwiched between two stators each containing 4 poles arranged equally along the circumference as seen in Figure 7 below. The positioning of probes leads to a 45-degree angle difference of them with radially adjacent poles. Preamplifier circuit is placed outside with the machine control elements. FEM analysis stated no magnetic flux was evident near the sensor probes. The proposed structure was manufactured which displayed good displacement and temperature characteristics. This arrangement claimed to reduce axial length by 9%, the influence of temperature on the circuit, enhance working frequency and stability of the high-speed machine. (Sun and Zhang 2014, Pp. 1950-1960.)

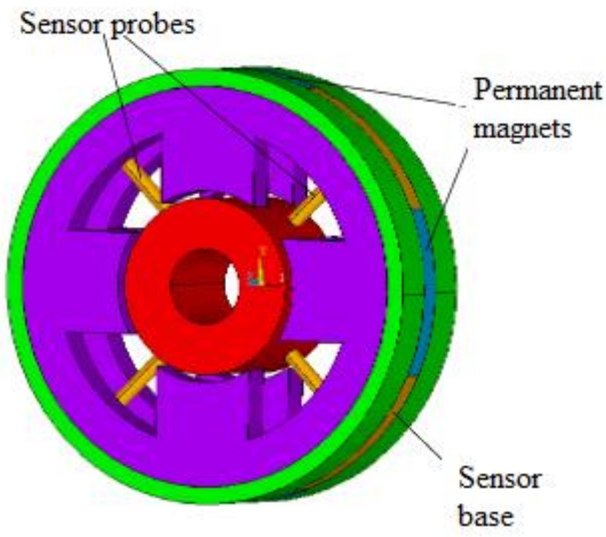


Figure 7. Eddy current sensors with permanent magnet integrated with an actuator (Sun and Zhang 2014, p. 1954).

Magnetic coils, which are manufactured from copper coils and wound manually around coil holders, are used in most sensors and actuators. The electrical connections between the magnetic coils are also made by hand. When hand assembly is needed, high output is not cost effective. US patent publication number US10,030,702 B2 mentions a magnetic bearing, comprising actuators and sensors in a single assembly as seen in Figure 8 below.

Actuator sub-assembly (2) is placed between two sensor sub-assemblies (4). Each sector (11) includes an actuator bobbin (20) and one magnetic sensor (30) when a sector of a sensor subassembly is considered. Compared to a single laminations stack, the bobbins can be larger thus load-bearing capacity is increased. The bobbins extend horns (16) which interact with the rotor. These are formed, combined with the curved part (12) by stacking lamination and manufactured by stamping. Curved parts (12) are made from stacking sheet metal and are connected with neighbouring curved parts by inserting pins (70). Polyamide plastic coil holder (22) on actuator and sensor bobbins comprise of coil made from enamelled copper. Aluminium rings (40) support magnetic sensors. Magnetic supports (50) are made from FeSi magnetic laminations. Coils are automatically wound around the holders (22) then bobbins are placed on the horns with automatization. Magnetic system mounting is easier and can be automatised which also improves electric and magnetic characteristics, owing to repetitiveness. This arrangement leads to labour time and cost reduction related to manufacturing. Also, modular construction makes the manufacturing process easier and faster. (Pat. US10030702 B2 2018, Pp 1-6.) Also, the possibility of employing this bearing to different sizes of machines is high, since not all pieces must be manufactured, only a few can be made in various sizes.

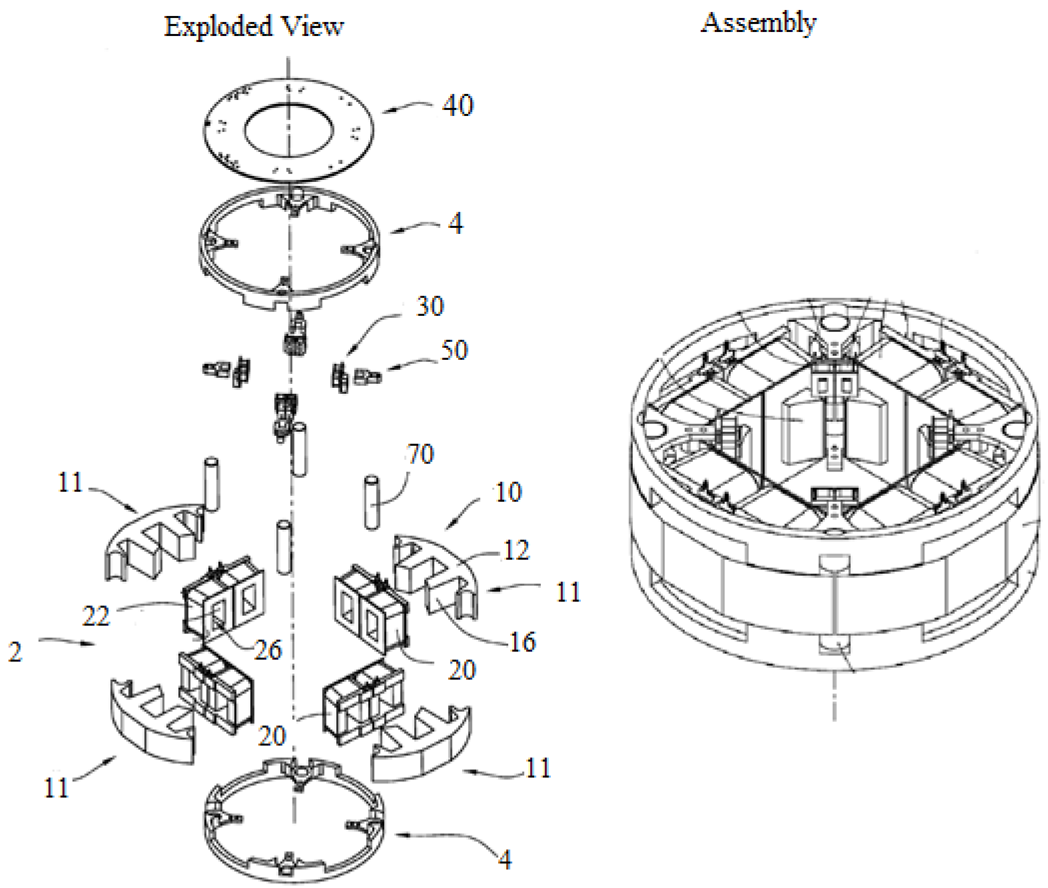


Figure 8. A magnetic bearing comprising of sensors and actuators in the same central assembly (Pat. US10030702 B2 2018, Pp. 1-2)**.**

An arrangement where low-cost eddy current sensors along with position servo control capable of estimation rotor position operational at high speed are presented. The actuator is made from laminated sheets (E-core) as seen in Figure 9. Magnetic force generation was assessed on a test setup. (Raghunathan and Logashanmugam 2019, Pp. 3481-3492.)

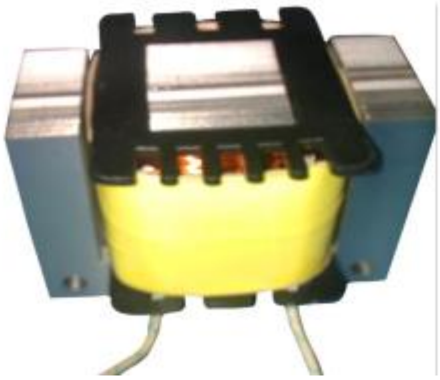


Figure 9. E- core type 32ctuator made from laminated sheets (Raghunathan and Logashanmugam 2019, p. 3484).

Eight actuators are placed on a steel structure in such a way that they can generate the axial force on a steel disc mounted on a rotor from either side. A sensor is placed at one end of the assembly facing the shaft in the axial direction as seen Figure 10 in below. The system with a digital PID controller was analysed and displayed good displacement resolution without errors. Better control and increased capacity are possible with modifications. (Raghunathan and Logashanmugam 2019, Pp. 3481-3492.)

This paves way for the possibility of using low-cost sensors in AMB assembly and the proposed. This might provide modularity and integration as each actuator is a separate unit, according to requirement the actuator could be modified to be employed in an AMB with different specifications.

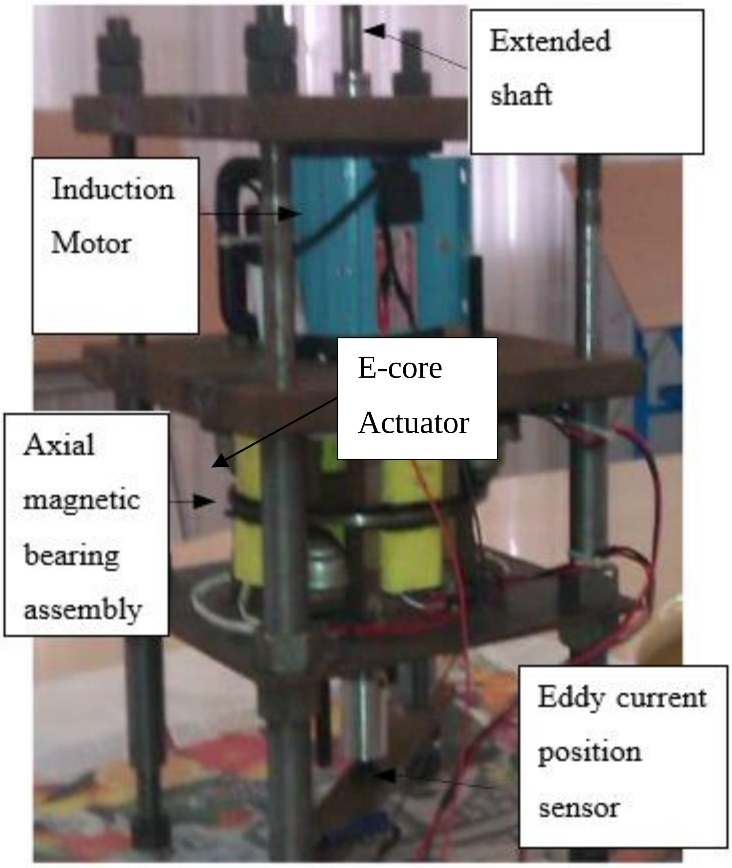


Figure 10. Test setup of axial AMB with low-cost eddy current sensors (Raghunathan and Logashanmugam 2019, p. 3487).

Another Eddy current sensor consisting of two sensing probes at one degree of freedom instead of one is presented. The sensor consists of a probe framework attached to a sensor circuit (PCB). This structure allows modularity with respect to the magnitude of winding on the probe coil and the possibility of placing the probe coil within the framework or screwing them until the required position is achieved. Coils are connected to preamplifiers on the PCB with non-shielded coils providing good signal transmission without losses owing to a short distance. Differential operation is achieved, reducing the impact of measurement error. Complimentary Benefits from this structure include sensor integrated bearing productization, convenient installation/assembly, hardware cost, and space requirement reductions. (Zhang Gang et al. 2011, Pp.373-384.)

Position sensor simulation using the Partial Element Equivalent Circuit (PEEC) method with varied excitation frequency and sensor layout led to the desired objective. Deviations in results were suspected to be due to measurement accuracy and scaling error. (Müsing et al. 2021, Pp. 1- 5.) This sensor possesses mechanical integration potential.

Another mechanical integration is performed by employing three inductive sensors equally along the circumference of an AMB stator. Stator core with 24 slots is occupied by three groups of magnetic force generating coils (1 – 6) and three inductive sensor coils (a, b, and c) as seen in Figure 11 below. The shaft position is estimated in three different axes 120 degrees apart from each other. Teeth between force-generating coils and sensor coils reduce magnetic influence inside sensor coils. Based on the determined second-order polynomial function of sensor coils inductance to the air gap, the position estimation algorithm is derived. Inductance to air gap function is generated using FEM. A new method to estimate position based on refined static and dynamic inductances gained from complex analytic of flux and current is presented. Along with accurate position estimation of the shaft, the radius of the same can be estimated. (Benšic et al. 2018, Pp. 1328–1341.)

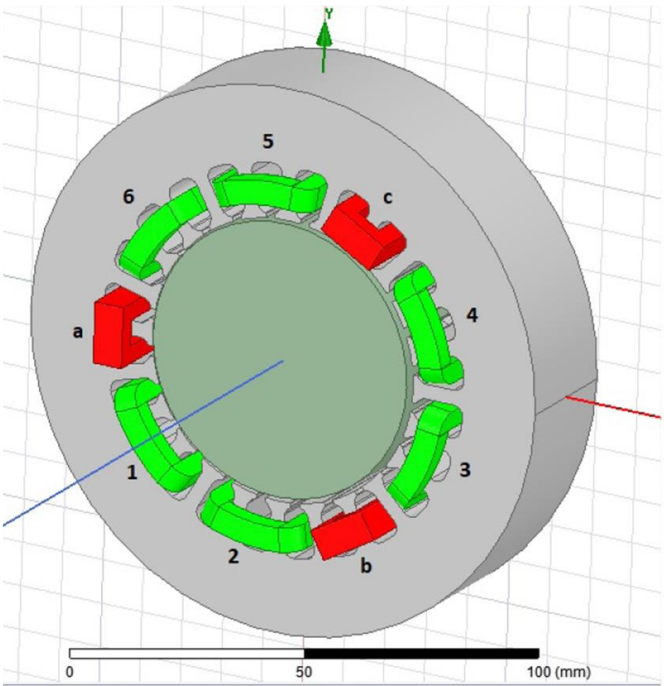


Figure 11. Arrangement of auxiliary coils for position estimation (Benšic et al. 2018, p. 1330).

This could be a possible mechanical integration solution where a minimum axial space requirement is demanded.

Ultrathin flexible sensors based on the Hall effect, which measure magnetic flux directly in the air gap between rotor and stator of an AMB, leading to precise and faster position estimation, were further optimized in terms of packaging in this research. Ernst et al. previously had studied the suitability of the bismuth printed on commercial polyimide PCB in AMB systems. The sensor was 150 micrometres thick, stable under applied thermal shocks and vibration. Information regarding optimized sensor manufacturing is provided in the article. (Ernst et al. 2020, Pp.39-43.)

The recent version of the manufactured sensor's thickness lies between 90 and 100 micro metres. Achieved via alterations in bonding tool design, joining method, and heat supply technique. The sensing side end is bonded to the stator pole with adhesive as shown in Figure 12 below. Good sensor characteristics were displayed with some noise. The author suggested few measures to reduce the same. Flexibility will facilitate easy assembly. Drastically reduce dimensions of the AMB. Incorporation of current AMB stators possible. The cost of realising must be considered. Suitability to various applications where AMBs are employed must be assessed. (Ernst et al. 2020, Pp.39-43.)

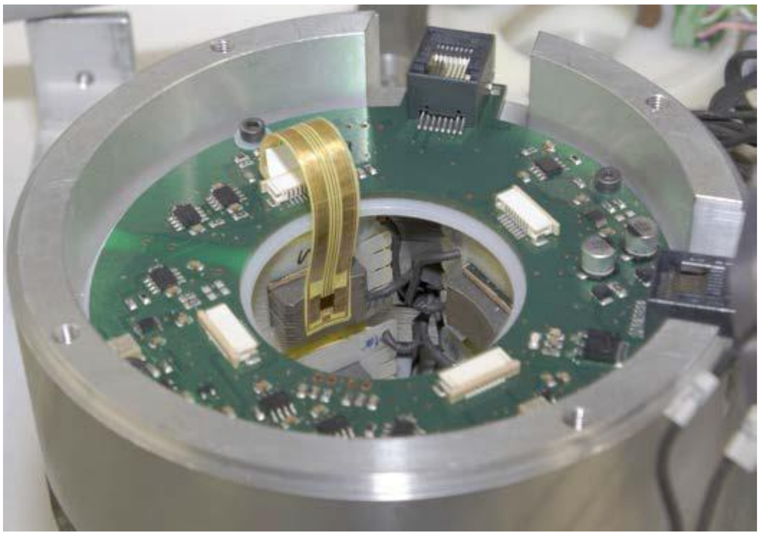


Figure 12. Hall effect sensors are placed along with actuators (Ernst et al. 2020, p. 42).

2.3.2 Sensor less technology for integration

This technique is playing a dominating role in providing sensor less rotor position estimation in AMBs to reduce the external sensing instruments and production costs. Here, the electromagnetic transducer is responsible for both actuation and sensing. To evaluate the position of the rotor, a self-sensing arrangement assesses bearing coil current and voltage waveforms. (Schammass et al. 2005, Pp. 509-516.)

Applications where the flexibility of the rotor is considerable, causing reversal of modal phase from the actuator to sensor due to presence of a flexible node between an actuator and its corresponding sensor lead towards instability. As sensor and actuator are identical in a self-sensing arrangement above mentioned situation is avoided. Few technical hurdles related to saturation and higher sizing to achieve the required amplitude of ripple were highlighted. Sensorless homopolar radial active magnetic bearing possessing attributes such as economic manufacturing and cost-effective operation owing to the coupling of standard electrical components and voltage source inverters was presented. A three-phase design was modelled with permanent magnets and analysed and simulated. A prototype was manufactured and tested with a solid and laminated rotor. The laminated rotor outperformed the solid rotor due to Eddy currents, noise, and material non-linearity. The authors stated further optimization is required to achieve better estimation.

Switching power amplifiers (PAs) used in most industrial AMBs generate intermittent perturbations or switching ripples in the coil currents. The ripple part uses modulation techniques to approximate rotor position. However, Band-pass filters (BPF) and low-pass filters (LPF) used to isolate and manipulate the high-frequency fundamental components, cause additional phase shifts and duty cycle alterations, affecting stability and position estimation adversely. Magnetic nonlinearity was used to create a new PA switching system that only calculated peak current ripple to obtain duty-cycle invariant location estimates to address the drawbacks mentioned above. (Niemann et al. 2013, Pp.12149-12165)

This approach was termed direct current measurement (DCM) in (Niemann et al. 2013, Pp.12149-12165; van Schoor et al. 2013, Pp.441-450). Various demodulation techniques were evaluated in a dynamic and static state and it was realised that DCM proves to be superior among all the techniques assessed with the least sensitivity and is suitable for incorporation in industrial applications (van Schoor et al. 2013, Pp.441-450). Another practical method was proposed where modulation was based on high-frequency voltage injection using pulse width modulation (PWM) power amplifiers. It should be noted that no compensation for duty ratio changes was required. Tests demonstrated good agreement between values received from sensors and the studied method. (Park et al. 2008, Pp. 1757-1764.) Further, a demodulation circuit capable of cancelling PWM is designed and dynamic performance was evaluated using frequency response analysis and validated with a magnetic suspension molecular pump. The results stated satisfactory speed, robustness and stability margin existed. (Jiang et al. 2019, Pp. 5460-5469.)

Sensorless technology offers various benefits such as reduced axial space, lower complexity of the application, hardware cost reduction, etc. but the operating range remains very narrow between 0 to 120 degrees Celsius (Waukesha Bearings 2021a). Schammass et al. stated that although various techniques are proposed to achieve self-sensing in AMBs, none of them leads to the realisation of a robust solution. A new self-sensing method is proposed along with an assessment of the possibility to be applied for industrial applications. It was found that the self-sensing technique estimates the position quite well for low frequencies, there are some discrepancies when it comes to high frequencies. To tackle this issue a new method was developed which estimates position based on low frequencies. This improved the estimation making it suitable for industrial incorporation, yet there exist some inferiorities compared to the standard sensor set, which is bandwidth, accuracy, and robustness due to magnetic material non-uniformity. A system with better magnetic permeability assessment capability would help overcome these limitations. (Schammass et al. 2005, Pp. 509-516.)

2.3.3 Hybrid integration solutions

A hybrid magnetic bearing capable of producing suspension in five degrees of freedom (DOF) is proposed. Two control radial windings were used to obtain suspension in 4-DOF (radial direction) along with compensating coils to avoid the influence of gravity. The structural configuration is shown in Figure 13 below. A permanent magnet ring wraps the inner stator and is sandwiched between axial control windings. The cylindrical rotor core is sufficient to achieve suspension in an axial direction, eliminating the need for a thrust disc.

This reduces the number of hardware components and volume of the bearing. A disturbance force in the radial direction is thought to twist the rotor away from its equilibrium position. The current is fed into the radial control wingdings, which bring the system back into equilibrium and produce the control flux based on the control requirement. Parameters, magnetic circuits, and design aspects of the structure are derived analytically. The power flux would be superposed on top of the PM-biased flux, resulting in a decrease in flux density and an increase in the right and left air gaps. The proposed model is then verified by computational check using 3D finite element analysis. (Yu et al. 2016, Pp. 1-17.) Experimental tests with a prototype would strengthen the suitability of this solution. This innovative solution provides a high degree of integration and could be employed where space constraints are present.

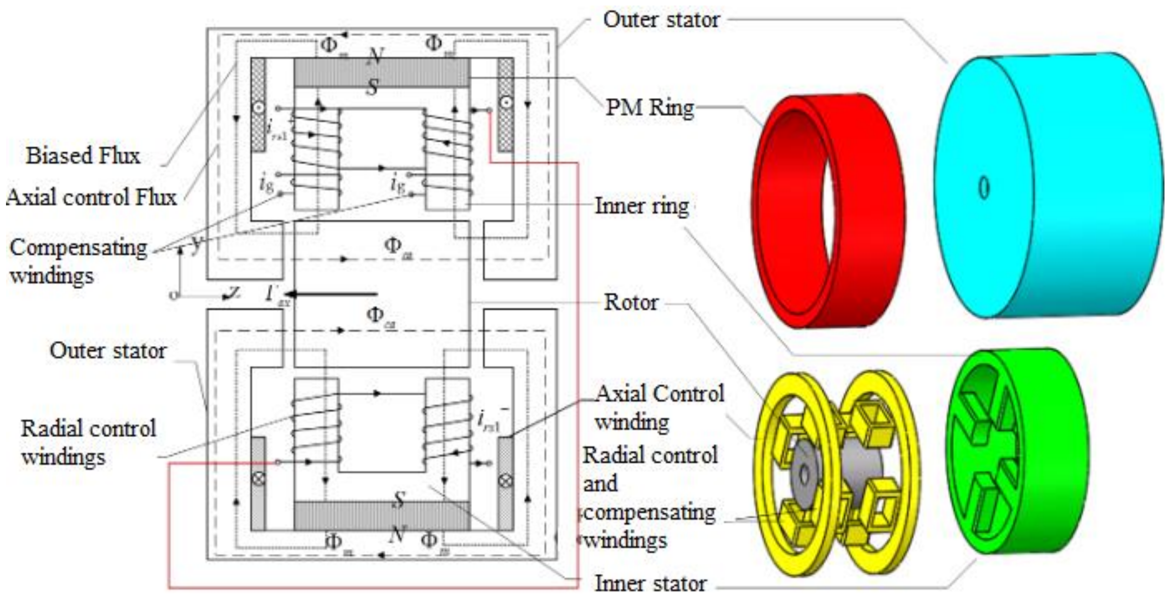


Figure 13. The structural configuration of the proposed hybrid magnetic bearing (Yu et al. 2016, p. 3).

Ren et al. proposed optimised high-temperature superconductor magnetic bearings possessing the potential of being studied for integrated structure as FEM analysis and verification stated good performance of improved design based on the magnetic field. The stator is made from three HTS rings each made from six yttrium barium copper oxide (YBCO) bulks. The HTS tapes manufactured can be up to 12 mm wide. HTS coils with the same currents are significantly smaller than the HTS ring in its whole. There is also the possibility of lowering cooling energy expenses. HTS tape coils having a greater average critical current density in volume, which may be used to improve bearing specific force characteristics. (Ren et al. 2019, Pp.1-5.)

There is a tiny superconducting layer on HTS tapes. Anisotropic characteristics of HTS tape, combined with complicated nonlinear properties, make it challenging to do a numerical study of magnetic systems using these HTS tapes It is necessary to enhance the methods of modeling elements formed of HTS tapes. (Kurbatova et al. 2020, Pp. 1-9). This technique after further improvements could reduce size of assembly while providing integration of components. As mentioned above active magnetic bearing provide damping and stiffness variation according to requirement. Also, better control is possible if accurate signals in a short time are achieved. In this paper use of nanotechnology-based sensors and actuators is proposed to achieve the same. Nanostructured sensors estimated the position faster and simulations results stated that it is robust enough to replace traditional ones. Further experimental analyses are required to verify the same. (Calderón et al. 2019, Pp. 1-8.)

2.4 DFMA analysis

Lucas DFMA method is used to analyze the product. As mentioned earlier the analysis will be carried out in two phases. In the first stage, ease of assembly will be assessed while manufacturability will be assessed in the second.

2.4.1 Desing for Assembly

In the case of assembly, as mentioned earlier analysis is carried out in three stages and the design for assembly analysis chart is used to analyse and records the outcomes of the analysis. The DFA chart is presented in section 2.4.1.

1. Functional Analysis:

Components are separated into two categories in this stage. Essential components, sometimes known as "A" components, are those that serve a key role. The "B" components, or non-essential components, having only secondary functions. These components are mostly used to support the "A" components, however, they can be discarded. The original aim for the design efficiency metric is 60%. (Kamrani and Nasr 2010, p. 152.)

If this is not possible, the first step in improving the design is to remove non-essential components. Design efficiency (DE) can be calculated as follows:

$$DE = \frac{Number\ of\ essential\ components}{Total\ number\ of\ components} \times 100 \qquad (1)$$

In Equation 1, The number of essential components is divided by the number of non-essential components and multiplied by 100.

2. Feeding/ Handling Analysis:

This ratio is used to evaluate component handling difficulties. The feeding/handling index is calculated using a part's size, weight, handling problems, and orientation. (Kamrani and Nasr 2010, Pp.152-153.)

$$Handling\ ratio = \frac{Handling\ index}{Essential\ number\ of\ components} \times 100 \qquad (2)$$

The feeding/Handling ratio is computed as described in Equation 2 above.

3. Fitting analysis:

The gripping, insertion, and fixing analyses are all part of the fitting analysis. Each part is assigned an index based on, fixturing requirements, insertion resistance force, and restricted eyesight during assembly. These measurements with high values suggest expensive procedures. The fitting index is a metric for determining the fitting ratio, which can be calculated by dividing the fitting index by the essential number of components. (Kamrani and Nasr 2010, p. 153.)

$$Fitting\ ratio = \frac{Fitting\ index}{Essential\ number\ of\ components} \qquad (3)$$

In Equation 3, the value of fitting ratios must be 2.5 ideally. Feeding/handling and fitting ratios indicate the effectiveness of a design. Numerous values according to the type of handling and fitting are gained from tables seen in Appendix 1, to calculate ratios mentioned above. (Kamrani and Nasr 2010, p. 154.)

2.4.2 Design for Manufacturing

To identify components based on their design features and material qualities, the Lucas DFM technique employs the idea of group technology. It calculates a "manufacturing cost index" which is used to assess the appropriateness of various production processes and operations. Note that the manufacturing cost index is directly proportional to the manufacturing cost. (Kamrani and Nasr 2010, p. 157).

$$M_{ci} = R_c P_c + M_c \tag{4}$$

The manufacturing cost index is calculated as seen in Equation 1, where M_{ci} is manufacturing cost index, P_c is primary processing cost and M_c is the total material cost (Kamrani and Nasr 2010, p. 157).

$$M_c = V C_m + W_c \tag{5}$$

Total material cost can be estimated using Equation 2, where V is material volume, C_m is the material cost (cost/volume) and W_c is the waste factor. The component's major processing cost is based on the idea of near net shape. The optimal primary process is chosen to achieve the component's whole (net shape) or significant design characteristics (near net shape). This procedure is chosen based on both design aspects and material properties, albeit material has the most influence. The incorporation of design complexity is the next phase in this process. This is used to investigate the relative cost of processing the elements that resulted in these complexities. R_c is calculated as described in Equation below. R_c is taken as unity if a net shape process is used. (Kamrani and Nasr 2010, p. 157)

$$R_c = C_c\, C_{mp}\, C_s\, C_t \text{ or } C_F \tag{6}$$

In Equation 6, C_c is the shape complexity, C_{mp} the material complexity, C_s the minimum section complexity, C_t the tolerance complexity, and C_F the surface finish complexity
The degree of shape complexity is decided based on, shape categorization into a rotational, prismatic, and flat wall. These are further classified depending on other characteristics, descriptions of these characteristics are presented in Table 2 below. Approximate values required to calculate the above-mentioned metrics to perform the analysis can be gained from tables as shown in Appendix 1 below. (Kamrani and Nasr 2010, p. 157.)

Table 2. Descriptions of characteristics (Kamrani and Nasr 2010, p. 157.)

Characteristics	Descriptions
Basic	Operation without a change of setting or tooling
Secondary features	Requires additional processing or more complex tooling
Multi-axis	Processed in multiple axis or setup
Non-uniform	Requires the development of a more complex process or setup
Complex	Requires dedicated tooling and specialized process
Single-axis	Axis along largest dimensions of the component
Through	Through features from one end or side to the other

2.5 Selection of productization solution

The selection of integration solution will be done by using a decision matrix built on Pugh's technique of concept selection as it needs the least number of comprehensive details, it is helpful in conceptual design selection and decision making. (Butt and Jedi 2020, Pp. 2-56.) This matrix assesses and rates the integration solutions, ultimately providing the best solution.

Selection criteria were considered based on various qualitative factors such as:

1. Number of parts
2. Design alterations required (Cost incurring)
3. Ease of manufacturing
4. Ease of assembly
5. Dismantlability
6. Assembly or manufacturing error correction
7. Mistake proofing
8. Automation Possibility
9. Ability to Sustain under operation condition
10. Modularity

The decision matrix was generated by inserting the selection criteria as columns, and the integration solutions are entered as rows. A neutral point is selected to serve as a benchmark against which all other ideas can be measured. In our case, the radial bearing and displacement sensor present in the AMB system developed under the HS-EDEN project at LUT will be considered a neutral point (Hakonen 2014, Pp 1-78). The explored solutions are evaluated against the neutral point

Integers +1, -1 and 0 are used to rate the solutions. The rating scheme is mentioned below:

- Where +1 means that the solution under consideration is superior to the neutral point.
- -1 means that the neutral point is superior to the respective solution in question.
- 0 means that the neutral point is neither superior nor inferior to the respective solution in question

The summation of the scores for each solution is calculated in the decision matrix and the most optimal solution was chosen based on the same. So that the solution with maximum pluses is selected. In the first iteration, the concepts which would not be employed are eliminated. However, the winning concepts may be under forming with minus scores or drub concepts might be excelling, with respect to one or more selection criteria. To gain a solution, performing well in most of the areas related to the selection criteria, in further iterations, new possible concepts formed by combining two or more concepts from the previous iteration are inserted as new columns and rated.

3 CASE STUDY: INTEGRATION AND DFMA SCHEME FOR AN ACTIVE MAGNETIC BEARING

This study is carried out to find the best integration scheme for an AMB. The framework followed for conducting the case study is shown in Figure 14 below. The components are analyzed using DFMA forms and tables. After analysis, the same are merged with possible solutions to generate new concepts. The selection matrix is used to gain the best integration solution via multiple iterations. It shall be noted that selection criteria also include DFMA principles. Hence, providing DFMA implementation. The proposed solution obtained via a selection matrix is analyzed, and the results are compared with those of the original design. The improvements gained are described to showcase the abilities of DFMA.

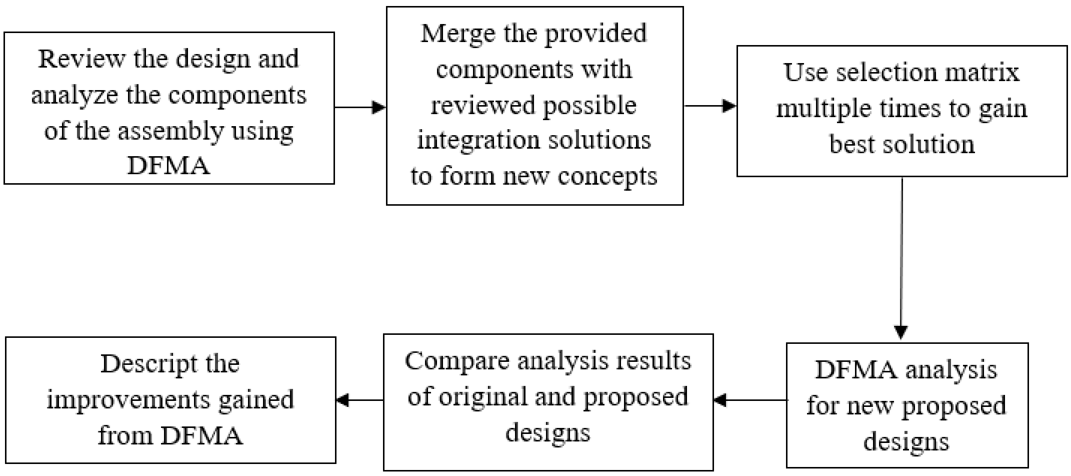


Figure 14. Framework for conducting a case study.

AMB developed for an HSM under the HS-EDEN project at LUT is considered as a case study (Hakonen 2014, Pp 1-78). We consider radial bearing on the clutch connection side as seen in Figure 16 below in exploded manner for DFMA analysis. DFMA analysis was carried on a radial bearing of the AMB system, which includes the sensor, actuator and parts required to realize the radial bearing assembly such as fasteners, holding plates and housings. Productization solutions to assemble and manufacture the displacement sensor and the actuator in a single unit were reviewed. The system consists of two radial bearings, one axial bearing, displacement sensors and a synchronous motor as seen in Figure 15 below. Stamped sheets are welded together to obtain the actuator stator core and sensor ring core. The stator core is inserted into the housing of the bearing plate and held in place using a bracket and fastened to the bearing plate using 4 screws. Two plates hold the sensor ring onto the axial bearing casing with the help of 6 screws.

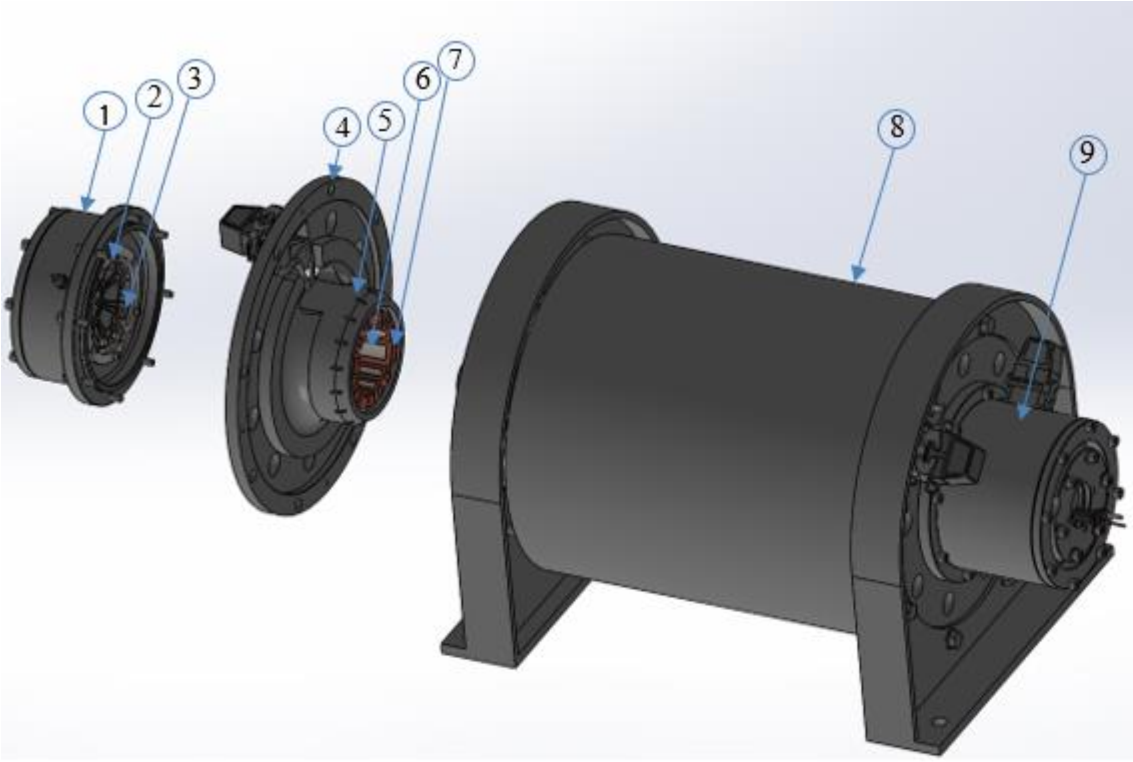


Figure 15. AMB system with motor (1) Radial bearing sensor casing, (2) radial position sensor ring holding semi-circular plate, (3) radial position sensor, (4) radial bearing plate, (5) radial bearing, (6) laminated stator core pole, (7) copper coils, (8) motor, (9) casing containing axial bearing and sensor along with second radial position sensor.

3.1 Design for Manufacturing and assembly analysis

The three-dimensional assembly provided by Spindrive was thoroughly examined using different modules present in SolidWorks to perform the analysis. Qualitative analysis can provide an overall image of assemblibilty and manufacturability of concerned radial bearing assembly.

3.1.1 Desing for Assembly

Table 4 below is used to analyze the radial bearing and sensor assembly. The chart enlists components and quantity along with functional essentiality, feeding, and fitting values of each component. The functional value is either A or B based on its essentiality as mentioned above. Components required to gain functioning of the AMB are considered as essential while the rest are considered as non-essential and tagged accordingly. For example, components such as screws are non-essential for the functioning of AMB, as some other methods such as welding, threading, shrink fitting, press fitting, etc. can be applied to fasten the casing and plates in the assembly.

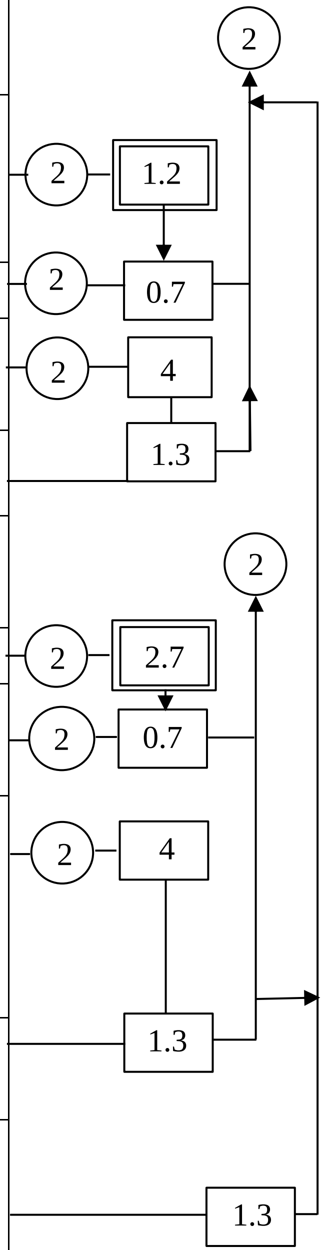
On the other hand, fundamental components required to achieve the function of the product that are copper coils, stator core, bearing plate, and casing are tagged as essential components. As copper coils and core generate the required attraction force while the bearing plate and casing support the same at the desired position. Values required to calculate the feeding/handling index are gained from the respective tables seen in Appendix 1 below based on size, orientation, weight, and handling difficulties of the components. The sum of the values obtained for each component from different tables is used to calculate the feeding/handling ratio. Similarly, the fitting index is calculated using fitting values which can be seen within the symbols of the flow diagram of the assembly in Table 4. The different shapes in the flow diagram represent the different types of processes as seen in Table 3 below. These values are estimated based on the type of manufacturing process, handling, and insertion method needed. (Kamrani and Nasr 2010, Pp. 152-155.)

Table 3: Flow diagram symbol description (Kamrani and Nasr, 2010, p. 153.)

Symbol	Process
◇	Gripping
○	Work handling
□	Insertion

Table 4. DFA analysis chart for the current arrangement.

Component	Component number	Quantity	Essentiality (A/B)	Feeding values
Bearing plate	1	1	A	2.4
Enamelled Copper coils	2	1	A	1.8
Stator core	3	1	A	1.5
Holding ring	4	1	B	1.2
Screws	5	4	B	1.2
Sensor casing	6	1	A	1.4
Sensor coils	7	1	A	1.8
Sensor stator core	8	1	A	1
Sensor semi-circular plates	9	2	B	1.9
Screws	10	6	B	1.2
Casing to bearing plate fastening screws	11	8	B	1.2



Total	11	27	6/11	16.6	33.2

Design efficiency and other ratios related to assembly analysis are calculated using Equations (1), (2), and (3) mentioned above. Note: Fitting index is the sum of all the values present in the flow diagram.

- Design Efficiency = 54.54 %
- Feeding/handling ratio = 2.7
- Fitting ratio = 5.53

The higher the design efficiency, the better the product. The number of parts of the product has a significant effect on the design efficiency value. The current analysis states the design is 54.54%. Chance of improvement as the aim should be above 60% as mentioned earlier. Attempts to improve Feeding/handling and Fitting ratios must be carried out. If the proposed design has better metrics, it automatically validates the proposed design gained from the selection matrix as a better alternative.

3.1.2 Design for Manufacturing

Table 6 describes the table used to perform the DFM analysis of the assembly. Columns representing volume and cost of the material per cubic millimetre are replaced with mass and material cost per gram to gain convenience regarding formulation (Alibaba 2021).
These values are easily available and can be inserted directly into the table without any need for performing calculations. Which make the implementation of this table convenient and quick. The goal of this study is to estimate the radial bearing assembly's manufacturing cost. It shall be noted that DFM analysis incorporated provides manufacturing index as an output which is a product of factors and actual material costs.

The assembly under study involves the use of standard components such as screws, whose costs are available in Euros. Hence, to avoid merging two values with different units, the costs of the standard components such as screws were gained from Alibaba formulation (Alibaba 2021). These costs are directly inserted into separate tables. Costs of standard components used in original assembly can be seen in Table 7. Both DFM analysis tables and tables with details about standard components will be reviewed at the end of the case study, to identify the most influencing parts of the assembly.

The purpose of this study is to improve the performance, functionality, and cost-efficiency of the considered assembly. It is assumed that ease of production and cost efficiency are the most important factors to consider while designing the bearing. The Lucas DFM study was carried out on a radial bearing assembly considering it as a benchmark or neutral point. The chart contains values of various aspects such as material complexity, shape complexity, primary processing, relative costs, and waste factor along with information such as mass, quantity, cost, and type of material regarding components of the assembly under consideration. With the above-mentioned values manufacturing cost index for each component was estimated. Volumes were gained from SolidWorks evaluate module and the cost of materials were obtained from an online store named Alibaba (Alibaba 2021).

Values such as shape complexity, material complexity and waste factor for each component were gained from the analysis tables, based on the type of material, shape, complexity and manufacturing processes required (Kamrani and Nasr 2010, Pp. 157-159). Some values were assumed for example regarding the primary cost factor, no evidence or guidelines for selecting a specific value for this factor was detected in the literature. To incorporate the primary cost factors, it was decided that the values corresponding to the number of manufacturing stages demanded by the component were used. In this manner the primary processing cost factor values are justified and a principle of DFM, stating manufacturing cost and time, being directly proportional to the number of manufacturing stages was included in the analysis (Eskelinen, 2020).

The components were manufactured by a sub-contractor. Hence, information regarding manufacturing processes, the number of stages applied, and other details are not available, but the same is estimated based on material type and grade, attributes of the components, literature, and Engineering knowledge as seen in Table 5 below. But it should be noted that the stock material required is usually more as it is available in standard sizes. There is some waste generated in the process of realizing components with desired dimensions. W_c accounts for this wastage based on the complexity of the shape and process required to achieve the component. Other mechanical operations are general and available in the literature, while the process of placing copper coils over the stator poles is rarely seen. Hence, the major steps of the process are described with the help of Figure 16. Where the insertion tool has slots to accommodate pre-winded bundles which are shifted from the tool over the stator poles with a pass the coils. There might be multiple passes involved based on the type of stator geometry.

Table 5 Number of manufacturing stages required for each component

Component	Number of manufacturing stages required	Description
Coils (sensor and actuator)	3	1. Making bundles of the copper coils 2. Fitting bundles over-insertion tool 3. Placing the coils over stator core poles by penetrating the insertion tool into the stator core.
Stator cores (sensor and actuator)	2	1. Stamping sheet metal 2. Welding the stamped workpieces together
Bearing plate	2	1. Casting 2. Machining
Touch down bearing and sensor casing	1	1. Casting 2. Machining
Sensor holding semi-circular plates	1	Laser/Plasma/Oxyfuel cutting
Stator holding ring	1	Laser/Plasma/Oxyfuel cutting

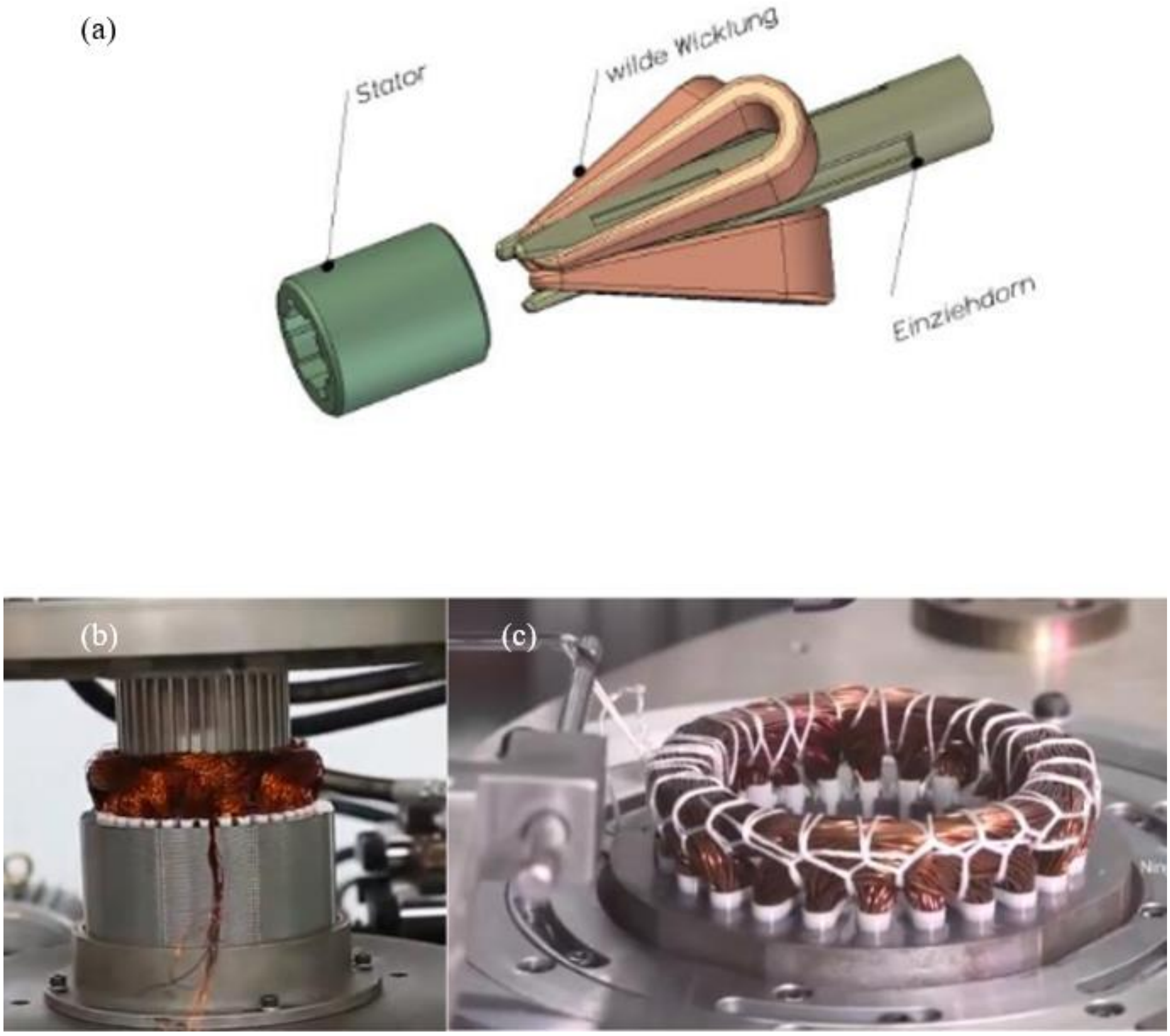


Figure 16. Copper coils fitment around stator poles (a) placement of coil over-insertion tool (b) insertion of the tool along with coils (c) lacing operation (Ningbo Nide Mechanical Equipment Co.,Ltd 2021; Wikiwand 2021).

Table 6 DFM analysis chart for the current arrangement

Components	Quantity	C_c	C_{mp}	Material	R_c	P_c	Mass (g)	W_c	Material cost/gram (€)	M_{ci}
Copper coil	1.00	1	1.20	Copper	1.2	3	3312	4	0.006	83.088
Stator core	1.00	1.20	1.50	Ferritic steel	1.8	2	7266	1.2	0.000703	9.729598
Bearing plate	1.00	3.20	1.00	Aluminum 6063	3.2	1	12529	1.4	0.00216	41.0877
Stator holding ring	1.00	1.00	1.50	Stainless steel	1.5	1	880	1.6	0.001838	4.087904
Sensor coils	1.00	1.00	1.20	Copper	1.2	3	302	4	0.005993	10.83954
Sensor stator core	1.00	2.50	1.50	Ferritic steel	3.75	2	663	1.2	0.000704	8.060102
Sensor stator holding semicircular plates	2.00	2.40	1.50	Stainless steel D200 PL10	3.6	1	320	1.6	0.001581	4.409472
Touch down bearing and sensor casing	1.00	3.20	1.00	Aluminium 6063	3.2	1	5039	1.4	0.002161	18.44499

Table 7 Details about standard components present in the assembly

Comments	Quantity	Type	Mass (g)	Cost (€)
Actuator Stator holding ring screws	4.00	DIN 912 M10	146.76	4.26
Sensor holding plate screws	6.00	DIN 912 M6	40.08	12.45
Casing fastening screws	8.00	DIN 912 M10	293.52	5.88
Total	18	-	480.36	22.59

3.1.3 Proposed improvements after DFMA

Two plates instead of one ring may be used for gaining modularity. But observing the geometry, the plates do not seem capable of accommodating sensor rings with large deviation in terms of diameter.

After analysing the AMB consisting of sensor and actuator, new concepts keeping in mind the DFMA principles are generated with the incorporation of features gained in the form of integration solutions from the literature review.

The selection process is iterative as mentioned earlier. Various solutions based on the methods enlisted below were proposed. The major type of methods considered was as follows: 1) Adhesive bonding. 2) Press-fit. 3) Thread fit. 4) Tolerance rings. 5) Snap rings. 6) Clamps. 7) Shrink fit and 8) Single stepped cylinder.

Among the above-mentioned assembly methods, the tolerance ring is a non-mainstream method. A tolerance ring is a custom-designed component that has waves, or other features, that are used to join cylindrical mating components. When the tolerance ring is assembled between the components, the waves compress to keep them in the desired position. (Saint-Gobain 2021.)
An example where a stator is mounted in a casing using a tolerance ring is seen in Figure 17 below.

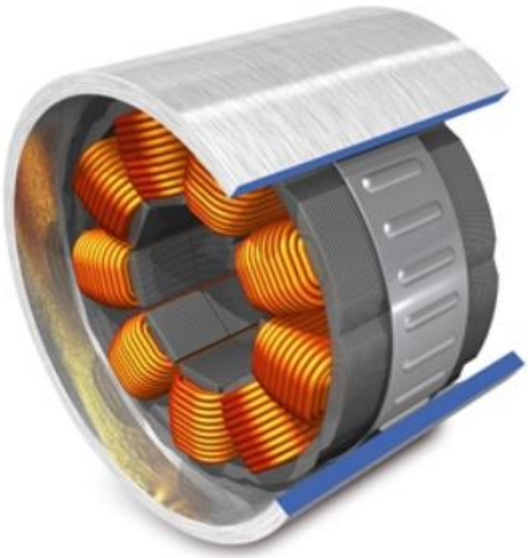


Figure 17. Stator fitted into the casing using tolerance ring (Tolerance ring stator mount, 2021).

A selection matrix was used to enlisting and comparing various arrangements for gaining the best integration solution as seen in Appendix 2. Where some were solely based on a single method while others were combinations of two or more. Table 8 presents notes regarding each solution. The notes are aligned with the criteria present in the selection matrix. It describes the reason for suitability or non-suitability.

Table 8 Proposed solutions and notes.

Solution	Notes
Stators shrink fitted	The number of parts, weight, and cost of assembly along with manufacturing are reduced.
Stators shrink fitted and mistake-proofing profile over casing/bearing plates and stators	With the above-mentioned benefits, the mistake-proofing profile helps to avoid mistakes and facilitates easy assembly
Welded plates and ring to casing and bearing plate respectively (steel to aluminium)	It creates a permanent joint. Also, joining different types of materials is not easy. Preparation is required and as being a thermal process chance of damage to components of assembly is present
Rings welded to hold the sensor and actuator sensor (change material to aluminium) with mistake-proofing profiles	Ease of welding due to similar materials used and easy assembly with mistake-proofing do not make it a top candidate owing to needs of design changes and above-mentioned demerits.
Adhesive bonding of rings (ring to hold sensor) and to hold the stators in place (steel)	Ability to sustain under operation conditions (200°C) (Kurvinen et al., 2021). Assembly error corrections would be time-consuming as a fresh adhesive application is required as the dried adhesive cannot be reused.
Adhesive bonding fitment of stators with mistake-proofing profiles	Along with the above-mentioned aspects related to adhesive bonding. Mistake proofing profile creation leads to additional manufacturing stages.
Single ring to hold the sensor	This will reduce the number of parts. But this will increase weight and efforts in terms of design changes.
Press-fit	It is a process where accurate tolerances need to be generated. It involves the use of force that might damage the stator. all these points make assembly and correction difficult.

Table 8 continues. Proposed solutions and notes.

Solution	Notes
Thread fit rings	The bearing plate design needs to be changed, so that space for threads could be generated and fitted with the rings. This increases manufacturing efforts. Also, modularity is quite low.
Snap rings	The bearing plate design needs to be changed, so that space for groove could be generated where the snap rings will be fitted.
Tolerance ring	The incorporation of tolerance rings reduces the number of assembly parts. Modularity and automation possibilities are low due to the customized nature. The same leads to difficult manufacturing. Spring-natured fit leads to difficult assembly.
Stepped cylinder	A cylinder fastened to bearing plate instead of the ring to provide multi-function of supporting actuator and sensor at the same time reduces parts. But weight due to design change is increased. There is a need to perform alignment of sensor stator during assembly making it difficult.
Clamps	This solution does not drastically reduce the number of parts. But provides modularity in terms of design change. These clamps can be used with different variants of AMB in terms of size. Also, they reduce material drastically providing weight reduction.

Firms providing solutions and services regarding tolerance rings were contacted to gain an estimated price for one tolerance ring for securing stator into bearing plate. The response indicated that this is not an off-the-shelf part and will be made for a specific application. Hence, the business will be undertaken only if the order is at least tens of thousands per year (Ludovic, 2021). Therefore, this option is good for high volume production and provides benefits such as reduced number of parts, low manufacturing, and assembly times, leading to cost-efficient operation. Shrink fitting is another method providing the same set of benefits and possessing limitations, which is discussed in section 3.2.1.

More research is needed in the case of assessing the suitability of adhesive bonding to gain answers for questions like will the bond and adhesive sustain subjected temperature and life of the machine. This creates partially permanent joints but is easier to disassemble when compared to welded joints. This also provides a little scope for modularity as no matter dimensional changes the adhesive is applied either between stator and mounting or in case of rings or plates used to hold the stator, the adhesive will be between the same and other casing or bearing plate surface. The bond between stator and bearing is not easy to be unbonded without causing damage to the components.

Welding the plates or rings to achieve the required fitment can induce thermal changes. More work and analysis to achieve welding without affecting the material properties of the stator are needed. Yet it creates a permanent joint that limits possibilities of correction, repair, service. Large forces are involved in a press-fit, causing damage, and inducing unwanted stresses which are not good for laminated structures under consideration. Chances of edges being damaged are high, leading to changes in performance. After, comparing the gained concepts for the solution, incorporation of clamps, shrink fitting, the addition of mistake-proofing features, use of a single ring to hold the sensor were found to be top-rated options. The best two conceptual solutions can be seen in Table 9 below.

Table 9 Selection matrix describing top rated proposed solution

Criteria	Current arrangement	Three clamps with Three screws at 120 degrees apart	Stators shrink fitted and into casing/bearing plates
Number of parts	N	+1	+1
Design alterations required (Cost incurring)	N	+1	+1
Ease of manufacturing	N	+1	+1
Ease of assembly	N	+1	+1
Dismantlability	N	+1	-1
Assembly or manufacturing error correction	N	-1	-1
Mistake proofing	N	+1	-1
Automation Possibility	N	-1	+1
Ability to Sustain under operation condition	N	+1	0
Modularity	N	+1	0
Total	N	6	2

3.2 DFMA analysis of new proposed designs

Further analysis on two top-rated solutions gained from the selection matrix seen above is carried out to assess the suitability of the same with respect to the radial AMB case under study.

3.2.1 Shrink fit

When it comes to housing stator interfaces, shrink fitting is a common practice. It is feasible to estimate an ideal shrink-fit pressure based on the sufficiently precise pressure-dependent coefficient of friction, thermal contact conductance, and core loss data. This will give adequate holding torque, low thermal contact resistance, and minimize the influence on core loss. However, because these parameters are impacted by several variables such as interface pressure, surface preparation, and temperature, they are difficult to estimate without the use of experimental methods. To avoid disassembly during operation, the working temperature range must also be determined. (Huang and Fang 2016, Pp.2766-2774.)

Heating the aluminium casing and bearing plate via induction would be wiser in our case as the bearing plate and casing are only to support. While performing any heating operation to the stators may cause changes in properties leading to inconsistent performance. The intention here is to heat the bearing plate at a temperature where the inner diameter is increased enough so that the stator could be inserted in. Later as the temperature drops the bearing plate will go back to the original shape. While doing so, it will close the gap and provide a good fitment of the stator inside the bearing plate.

This way, the number of parts, weight, and cost of assembly along with manufacturing is reduced. If the coefficient of thermal expansion is known, the amount that a particular metal will expand can be calculated using the following equation:

$$d = aL(dt) \tag{7}$$

In Equation 7, d is the total deformation desired in mm, a is the coefficient of thermal expansion in $10^{-6}/°\mathrm{C}$, L is the circumference of the cylinder in mm and dt is the temperature difference.
Modifying this equation to gain temperature difference gives us an Equation as seen below:

$$dt = \frac{d}{aL} \tag{8}$$

In Equation 8, d = 1 mm, a = 23 × 10^{-6}, L = 530.92 mm. Therefore, the temperature difference is 103 °C Considering the initial temperature as 40 °C, The total heat needed to be provided for the bearing plate is 143 °C.

After discussion with technical experts from industries providing shrink-fit via induction, the above-mentioned values were verified. The values gained from experts for the case under study were close to the calculated value using Equation 8 above. (Jasper, 2021; Leskinen, 202). The induction setup suggested by the technical entity was rated 25 kW. To achieve the required heating of the bearing plate, it needs to be heated for 3 minutes. The cost that will incur for shrink fitting once stator inside bearing plate can be obtained by calculating the energy consumed by the generator required to heat the bearing plate. As we know energy is a product of time and power.

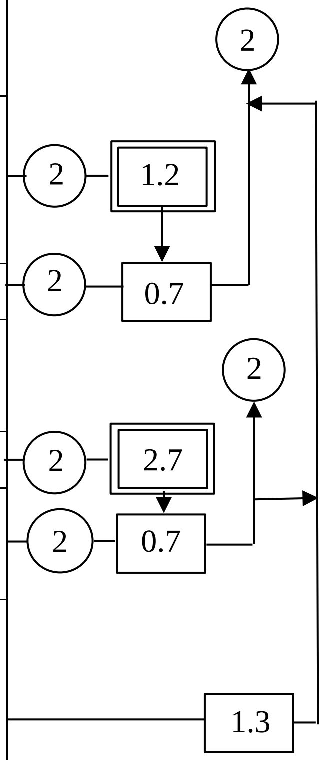
Thus, the cost can be calculated by using this relation after setting the units of the available parameters and following the steps mentioned below:

- Converting the operation time in terms of hours
  3 minutes = 0.05 hours
- Gain power value in kWh
  0.05 x 25 = 1.25 kWh
- Multiply the same with per hour rate of electricity
  1.25 x 0.10 = 0.125

0.125 euros will be the cost incurred to shrink fit. Note that even though the cost of operation is low. But the initial cost of induction machine setup is high. Also, the possibilities for employing the same setup for other variants of bearings is not favourable, as the heating coils are custom made for accurately heating a specific component. (Jasper, 2021; Leskinen, 2021). The DFA, DFM analysis, and cost of standard components can be seen in Table 10, Table 11, and Table 12 respectively. This solution is suitable for a product whose dimensions won’t vary much and are to be made in bulk.

Table 10 DFA analysis for proposed solution employing shrink fit

Component	Component number	Quantity	Essentiality (A/B)	Feeding values
Bearing plate	1	1	A	2.4
Enamelled Copper coils	2	1	A	1.8
Stator core	3	1	A	1.5
Sensor casing	6	1	A	1.4
Sensor coils	7	1	A	1.8
Sensor stator core	8	1	A	1
Casing to bearing plate fastening screws	11	8	B	1.2



Total	7	14	6/7	11.1	18.6

- Design Efficiency = 85.71 %
- Feeding/handling ratio = 1.83
- Fitting ratio = 3.1

Table 11 DFM analysis for proposed solution employing shrink fit

Components	Quantity	C_c	C_{mp}	Material	R_c	P_c	Mass (g)	W_c	Material cost/gram (€)	M_{ci}
Copper coil	1.00	1	1.20	Copper	1.2	3	3312	4	0.006	83.088
Stator core	1.00	1.20	1.50	Ferritic steel	1.8	2	7266	1.2	0.000703	9.7296
Bearing plate	1.00	3.20	1.00	Aluminum 6063	3.2	1	12529	1.4	0.00216	41.0877
Sensor coils	1.00	1.00	1.20	Copper	1.2	3	302	4	0.005993	10.8395
Sensor stator core	1.00	2.50	1.50	Ferritic steel	3.75	2	663	1.2	0.000704	8.0601
Touch down bearing and sensor casing	1.00	3.20	1.00	Aluminium 6063	3.2	1	5039	1.4	0.002161	18.445
Total	6.00	12.10	7.40		14.4	12.00	29111	13.2	0.017721	171.25

Table 12 Details about standard components present in the assembly

Component	Quantity	Type	Mass (g)	Cost (€)
Casing fastening screws	8.00	DIN 912 M10	293.52	5.88

3.2.2 Incorporation of clamps

Table clamps are generally used for clamping workpieces on machining tables or other components such as optical components on breadboards. An example of one such breadboard clamp is seen in Figure 18 below (Table Clamps, 2021.)

Figure 18. Thorlabs table clamps (Table Clamps, 2021).

Clamps are also used in metal removal manufacturing processes such as milling to hold the workpiece to the table. These clamps can hold different types of workpieces in terms of size and shape. Two types of clamps based on the type of machining conditions are plane and stepped clamps. Where the steeped clamp is shown in Figure 19 (a) uses a stepped block to provide usability with different kinds of workpieces in terms of height. On the other hand, the plane clamp seen in Figure 19 can be used when a block with the same height as that of the workpiece can is available. The function of these clamps can be seen in Figure 20 below

Figure 19. a. Stepped clamps (left) b. Plane clamps (right) (STEP CLAMP | SUPER TOOL CO., LTD. 2021).

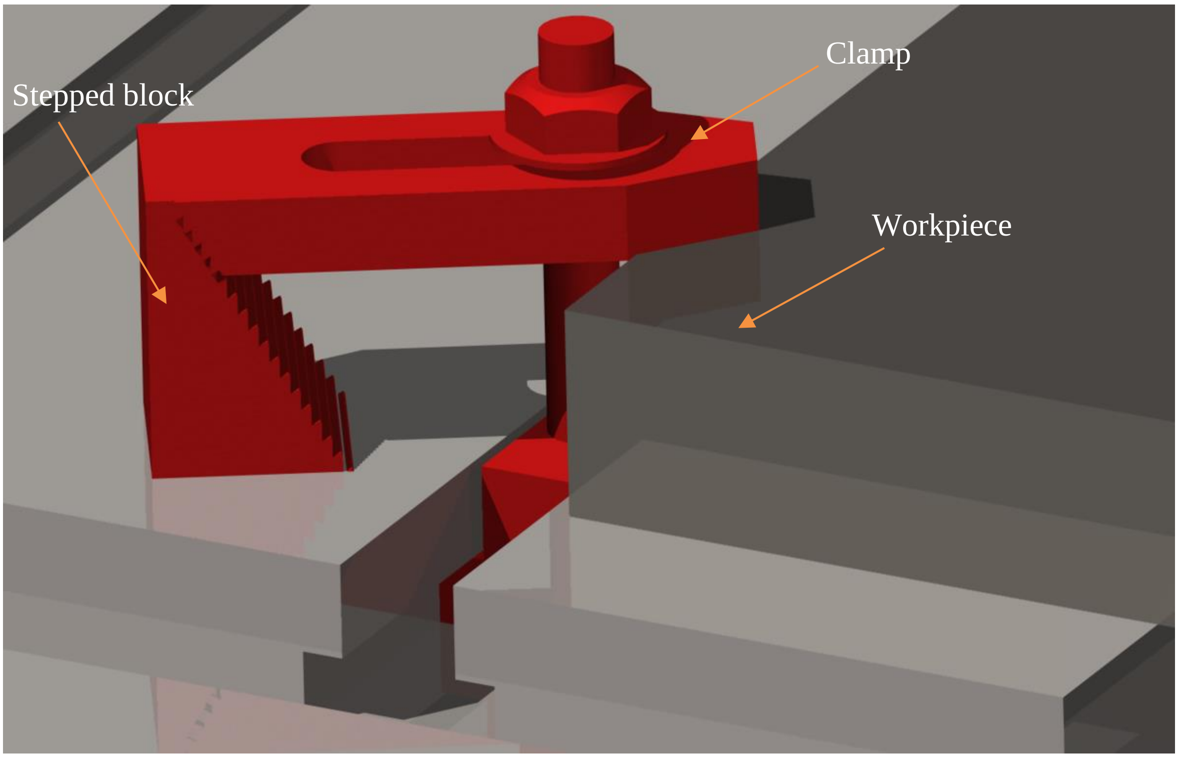


Figure 20. The function of a clamp in machining

Inspired by these clamps we designed a basic clamp that will hold the actuator stator and sensor ring in place with the help of M6 screws fastened to the bearing plate and casing respectively. The designed clamp and proposed arrangement with respect to casing can be seen in Figure 21 (a) left and (b) right below respectively.

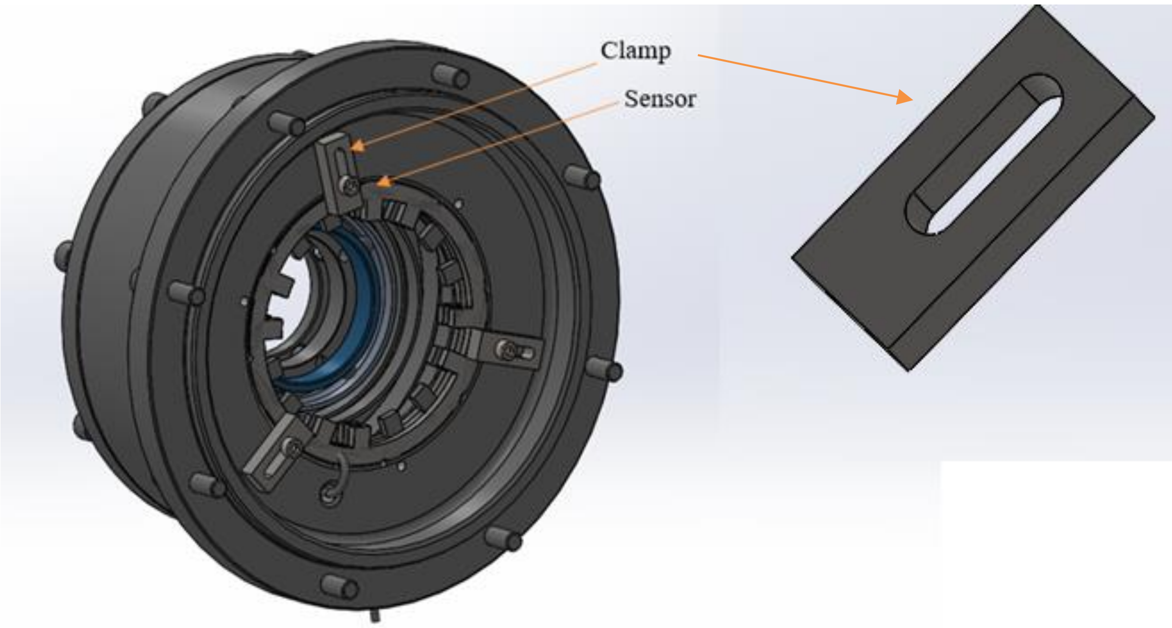


Figure 21. 3D models of the proposed arrangement of a basic clamp with respect to the casing.

The use of three clamps placed radially 120 degrees apart was proposed to hold the actuator and sensor stators, instead of ring and semi-circular plates. The arrangement of the clamps with respect to the bearing plate can be seen in Figure 22 below. This solution does not drastically reduce the number of parts. But provides modularity in terms of design change. These clamps can be used with different variants of AMB in terms of size. Also, they reduce material drastically providing weight reduction.

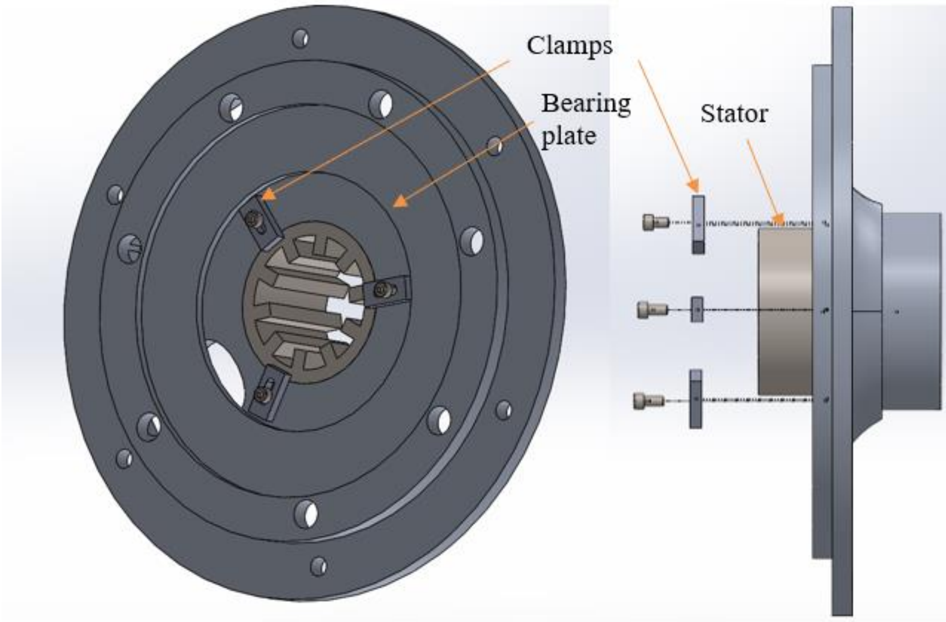
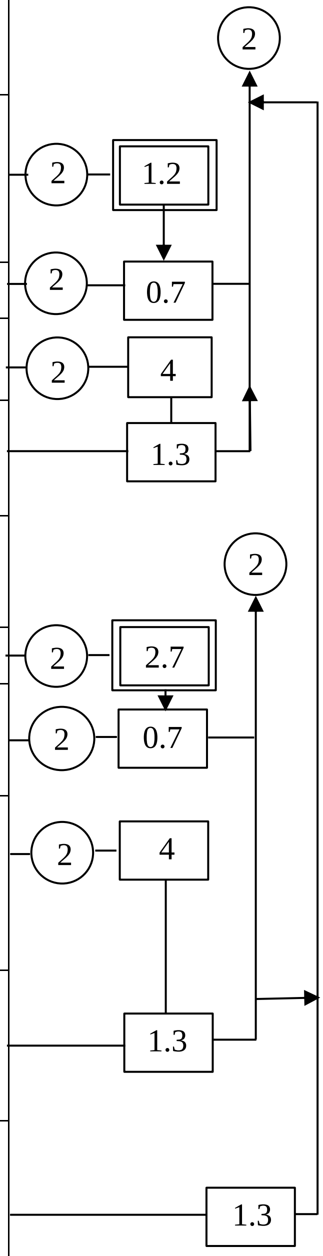


Figure 22. Proposed assembly for actuator within bearing plate using clamps a. normal view (left) b. exploded side view (right).

Clamps are suggested to be manufactured using machining processes. For the DFM analysis for this case, the mass properties are achieved from SolidWorks and the material price of the clamps is obtained from Alibaba (Alibaba 2021). The DFA, DFM analysis, and cost of standard components can be seen in Table 13, Table 14, and Table 15 respectively

Table 13 DFA analysis for proposed solution employing clamps

Component	Component number	Quantity	Essentiality (A/B)	Feeding values	
Bearing plate	1	1	A	2.4	
Enamelled Copper coils	2	1	A	1.8	
Stator core	3	1	A	1.5	
Clamps	4	3	B	1.1	
Screws	5	3	B	1.1	
Sensor casing	6	1	A	1.4	
Sensor coils	7	1	A	1.8	
Sensor stator core	8	1	A	1	
Clamps	4	3	B	1.1	
Screws	5	3	B	1.1	
Casing to bearing plate fastening screws	11	8	B	1.2	
Total	9	26	6/9	15.5	33.2



- Design Efficiency = 66.66 %
- Feeding/handling ratio = 2.58
- Fitting ratio = 5.53

Table 14 DFM analysis for proposed solution employing clamps

Components	Quantity	C_c	C_{mp}	Material	R_c	P_c	Mass (g)	W_c	Material cost/gram (€)	M_{ci}
Copper coil	1.00	1	1.20	Copper	1.2	3	3312	4	0.006	83.088
Stator core	1.00	1.20	1.50	Ferritic steel	1.8	2	7266	1.2	0.000703	9.7296
Bearing plate	1.00	3.20	1.00	Aluminum 6063	3.2	1	12529	1.4	0.00216	41.0877
Sensor coils	1.00	1.00	1.20	Copper	1.2	3	302	4	0.005993	10.8395
Clamp	6.00	1.00	1.50	Stainless steel 316 L	1.5	1	244.74	1.6	0.00036	1.64097
Sensor stator core	1.00	2.50	1.50	Ferritic steel	3.75	2	663	1.2	0.000704	8.0601
Touch down bearing and sensor casing	1.00	3.20	1.00	Aluminium 6063	3.2	1	5039	1.4	0.002161	18.445
Total	12.00	13.10	8.90		15.9	13.00	29356	14.8	0.018081	172.891

Table 15 Details about standard components present in the assembly

Components	Quantity	Type	Mass (g)	Cost (€)
Sensor and actuator holding clamp screws	6.00	DIN 912 M6	244.74	12.45
Casing fastening screws	8.00	DIN 912 M10	293.52	5.88
Total	14	-	538.26	18.33

4 RESULTS AND DISCUSSION

After reviewing the possible productization solutions and the case study assembly. It was decided in the initial stage that a selection matrix shall be used to compare generated solutions to gain the best out of them based on DFMA and qualitative factors. It was observed that few aspects were already evident in the design for example use of standard components, the minimum number of assembly directions, etc. While the design lacks in some areas such as modularity, mistake proofing, the minimum number of parts, self-positioning, the principle of product families, simplicity of design, weight reduction, ease of assembly and manufacturing, etc. These aspects along with others were desired in the proposed design.

Based on available data and after conducting a literature review it was decided that the Lucas method would be suitable for analysing radial AMB assembly. The technique was altered in several ways to make it more suitable for use based on the availability of data and the nature of the product to be analysed. DFMA analysis was conducted on original assembly and two top-scoring proposed solutions are listed below:

1. Proposed solution employing shrink fit
2. Proposed solution incorporating clamps

The results from DFMA analysis of top-rated conceptual solutions and original assembly are combined and presented in Table 16 below.

Table 16 Comparison of the proposed concept solution with the original arrangement.

	Current arrangement	Shrink fit	Incorporation of clamps
Design efficiency	54.54 %	85.71 %	66.66 %
Number of parts	27	14	26
Handling index	2.7	1.83	2.583
Fitting index	5.53	3.1	5.53
Mass (g)	30791.36	29404.52	29893.96

Table 16 continues. Comparison of the proposed concept solution with the original arrangement

	Current arrangement	Shrink fit	Incorporation of clamps
(MI) Manufacturing cost index	179.747	171.25	172.89
Cost of standard components (€)	22.59	5.88	18.33
Sum of (MI) manufacturing cost index and cost of standard components	202.337	177.13	191.22
Number of different types of components	11	7	9

The number of components of the original assembly is reduced from 27 to 26 and 14 in the case of solution where clamps are used and where shrink fitting is used respectively The design efficiency of solution with shrink fitting is highest at 85.71 %. That of the solution with clamps is 66.66 %, while the original assembly is 54.54 %.

Mass of the assembly is reduced with the use of clamps and incorporating shrink fit. Total weight is reduced by 1.38 kg and 0.89 kg by employing shrink fit and clamps respectively. Handling and fitting indexes have been improved in the case of shrink-fitted assembly. Both manufacturing cost index and cost of standard components are lowest with shrink fitted assembly. Note that even after adding the cost of electricity i.e., 0.125 euros, required to generate the induction energy for shrink fit along with the cost of manufacturing, this is the most cost-efficient solution. The cost of standard components required with shrink fitting is less than 50% when compared to the original assembly and solution with clamps.

Observing Figure 23 below it is clear that shrink fitted assembly is the best integration solution for assembling radial bearing actuator and sensor. We can infer that cost of net material used in the bearing assembly is not very expensive. But it should be noted that the stock material required is usually more as it is available in standard sizes.

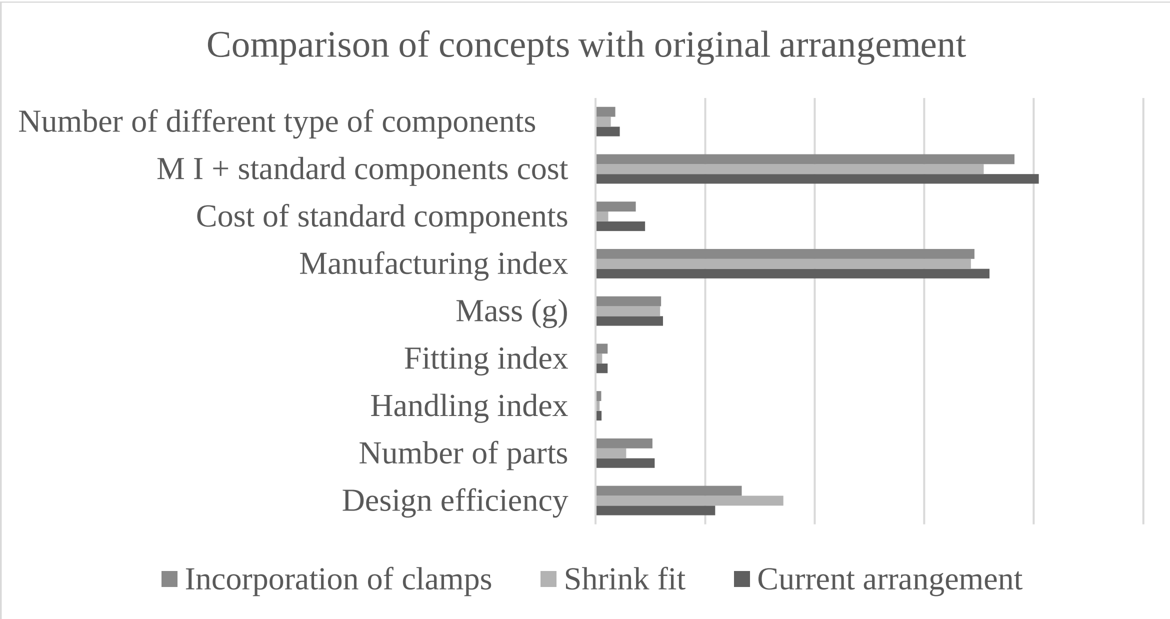


Figure 23. Comparison of proposed concept solution with the original arrangement.

There is some waste generated in the process of realizing components with desired dimensions. W_c accounts for this wastage based on the complexity of the shape and process required to achieve the component.

Also, shrink fit also eliminates the need for machining holes and threads. Along with all the mentioned benefits it shall be noted that the initial investment of shrink fitting is as high as 50,000 Euros. Also, this machine is tailored for specific products. This leads to lower flexibility. Although for the high-volume production of a single product, this might be the best option. But further research and tests are necessary for assessing the feasibility of this method and accurate values of parameters in case of an AMB. The shrink fitting solutions providing firms offer laboratory testing service when samples are provided by the willing customer (Jasper, 2021; Leskinen, 2021.)

The manufacturing cost index is the product of material cost, where material costs are in euros gained from an online store, factors depending upon processes required, and other attributes of the component. Therefore, the manufacturing cost index is an estimation.

In the case of a solution where clamps are used, even if we don’t see much difference in the manufacturing cost index and the total number of components when compared to original assembly, it should be noted that it does not involve high initial investments and provides immense modularity. This solution only incorporates six M6 type screws for fastening both sensor and actuator, eliminating the need for four M10 screws. This improves the universality and interchangeability of the assembly. The obvious question would be that will these clamps be able to provide the required holding force. As already mentioned, these kinds of clamps are used to hold workpieces on the table while machining operations like milling involve a high number of forces. Ideally, radial bearing experiences load in a radial direction. Clamps would sufficiently hold the stator of an actuator in place. But yes, further analysis with the help of modelling and simulations shall be done to verify if this solution will sustain under operating conditions. In the case of a sensor where no load is experienced, this scheme could be directly applied.

It was evident that two criteria that are manufacturing ease and mistake-proofing profile, zeroed each other out as to make a self-positioning profile to avoid mistakes, more manufacturing efforts are required. Changes in product design have effects on the product family. In this research, we have considered a prototype built at LUT. In the case of an industrial product, the effect of changes and improvements gained via DFMA application on product families must be considered as the improvements may be advantageous for an analysed product. But might affect other products of the family adversely. Another question would be why was DFMA analysis is performed if all the information such as assembly times, manufacturing costs, etc. was not available. It was performed to provide a guide for readers keen to perform reverse engineering to improve the product without having all the information about the product.

With his method analysis of only components obtained from conventional processes is possible. Many changes were made to the DFM analysis table to fit the same with the assembly under study. Some articles mention the use of LUACS TeamSET software for DFMA analysis but after searching and enquiring no fruitful results were obtained.

literature about possible options for sensor and actuator integration is reviewed. Using the stator of a motor as an AMB stator, including common industrial components, using configuration design, and collaborative assembly are some ways for improving AMB and other mechatronic devices in terms of manufacturability and assembly.

Self-sensing AMBs in a true manner inherits DFMA aspects by the means of its working principle. In this type of AMB, both sensing and actuation function are performed by a single set of coils. This reduces the number of parts and space required, making the assembly lighter and smaller. Other solutions such as employing Hall effect sensors, PCB embedded sensors, etc. have the potential to provide an improved and integrated AMB but, need further research to be turned from concept to commercial solution.

5 CONCLUSION

Also, very little information about the manufacturing and assembly of AMB is available when compared to the design part. No articles dealing with DFMA of AMB or review of a possible solution for integrating sensors and actuators are present. Maybe because the cost of hardware used in an AMB is low, not much emphasis on cost reduction of manufacturing is given. Engineering work such as designing, and testing needed leads to a higher price of the AMB. AMB is still treated as a custom component tailored for a specific machine to obtain the best performance. Also during a discussion with Spindrive, when asked about previous attempts taken regarding DFMA, the response was such that performance is emphasized more.

As stator of a motor and AMB somewhat share similar mechanical structure. Hence, values related to manufacturing processes, tools, material information, etc. can be used for analysis. SolidWorks is a tool that can help with finding the values such as, weight, dimensions, etc., needed for DFMA analysis if a 3D model is available. Accuracy of results from DFMA analysis and availability of data related to assembly and manufacturing are directly proportional to each other. Hence, companies should maintain quantitative data regarding assembly and manufacturing for future accurate analysis. This thesis will serve as a guide for readers interested in using reverse engineering to enhance a product without knowing all of the product's details.

Lucas DFMA method demands fewer data and leans more towards qualitative or functional analysis. Lucas DFMA method we followed gave factors related to only non-advanced methods. For current times and mechatronic assemblies where advanced methods like laser processing, additive manufacturing, etc. are used. Also, parts such as coils, wires etc. are not suitable for the current DFMA analysis method. In the case of a mechatronic product usually, DFMA is only performed for structural parts. Revamp of this method is necessary so that it could be applied to products of present and future age as it can help make the assembly and manufacturing easy. As mentioned earlier AMB is still not an off-the-shelf product. Hence, it will be made on an order as per requirements to provide the best performance. In doing so there are chances that the dimensions change. Although shrink fitting scores well in all the areas, there are some things to be considered before adopting this scheme such as high initial investment, lower flexibility to design changes, thermal changes, etc.

But if the product is of a high-volume nature and tests prove the feasibility, this is the most cost-efficient and best solution in long run. DFMA analysis shall be performed with an open mindset, i.e., not always following thumb rules but also thinking out of the box. Also, knowledge of multiple fields shall be available to avoid disregarding functional requirements while selecting alternatives.

It is possible to make manufacturing and assembly easy without reducing the number of parts. In the case of the solution with clamps, we can see that it provides high modularity. It can be employed in any machine to hold the AMB actuator and sensor in place with changes in dimensions. Also, it reduces the need for material making the assembly lighter. Verification of the proposed solutions with different joining methods to assess suitability for subjected operation conditions shall be performed. In the end, selection depends on desired requirements from the product for example modularity or production time and type of production. Also, an attempt to reach a compromise to gain some degree of all the attributes is possible.

Solutions gained from DFM are estimations, further analysis with other methods or software to gain better and accurate results is necessary. Another widely used DFMA analysis method known as Boothroyd-Dewursht shall be used in future when quantitative data is available.
Self-sensing AMBs in a true manner inherits DFMA aspects by the means of its working principle. In this type of AMB, both sensing and actuation function are performed by a single set of coils. Other solutions such as employing Hall effect sensors, PCB embedded sensors, etc. have the potential to provide an improved AMB.

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Meaning of symbols used in fitting analysis flowchart (Kamrani and Nasr, 2010, p. 153)

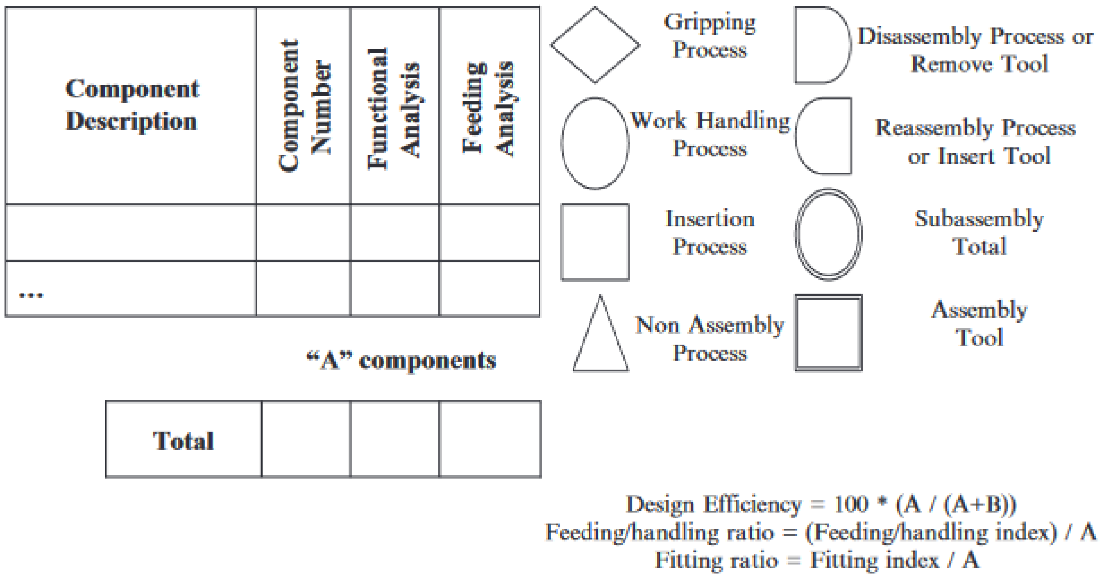

Fig. 6.10 LUCAS DFA assembly analysis chart

Table 6.4 Size and weight analysis

Very small	Requires handling aids	1.5	Select one for *A*
Easy	Requires one hand only	1	
Large and/or heavy	Requires more than one hand or grasping aid	1.5	
Large and/or heavy	Requires more than one person or hoist	2	

Tables containing values required for DFA analysis (Kamrani and Nasr 2010, p. 154)

Table 6.5 Handling analysis

Delicate	0.4	Select all applies for *B* ($B = 0$ if delivered automatically)
Flexible	0.6	
Sticky	0.5	
Tangle	0.8	
Severely nested	0.7	
Sharp	0.3	
Untouchable	0.5	
Gripping problem	0.2	

Table 6.6 Orientation analysis

Orientation along the axis of insertion		Select one for *C*
Symmetrical – no orientation required	0	
Easy to see orientation – end to end	0.1	
Not easy to see orientation – end to end	0.5	
Rotational orientation along the axis of insertion		Select one for *D*
Rotational symmetry not required	0	
Easy to see rotational symmetry – end to end	0.2	
Not easy to see rotational symmetry – end to end	0.4	

Tables containing values required for DFA analysis (Kamrani and Nasr 2010, p. 154)

Table 6.7 Part placing and fastening analysis

Part placing analysis		Select all applies for A
Self-holding	$M = 1.0, A = 1.0$	
Holding down required	$M = 2.0, A = 1.2$	
Part fastening analysis		
Self-securing	$M = 1.3, A = 1.1$	
Screwing	$M = 4.0, A = 1.0$	
Riveting	$M = 4.0, A = 1.3$	
Bending	$M = 4.0, A = 1.6$	

M, manual; A, automated

Table 6.8 Direction analysis

Straight line from above	$M = A = 0$	Select one for B
Straight line not from above	$M = 0.1, A = 0.2$	
Not straight line – bending required	$M = 1.6, A = 1.2$	

M, manual; A, automated

Table 6.9 Insertion analysis

Single	$M = A = 0$	Select one for C
Multiple	$M = 0.7, A = 1.2$	
Concurrent	$M = 1.2, A = 1.2$	

M, manual; A, automated

Tables containing values required for DFA analysis (Kamrani and Nasr 2010, p. 155)

Table 6.10 Access, alignment, and resistance analyses

Restricted access and/ or vision	$M = 1.0, A = 0$	Select one for D
Difficult to align		Select one for E
Yes	$M = 0.7, A = 0.8$	
No	$M = A = 0$	
Resistance to insertion		Select one for F
Yes	$M = 0.6, A = 0.8$	
No	$M = A = 0$	

M, manual; A, automated

Table 6.11 Non-assembly process analysis

Additional screwing	$M = 4.0, A = 1.0$	Select all applies
Mechanical deformation	$M = 4.0, A = 1.0$	
Soldering/welding	$M = 6.0, A = 1.6$	
Adhesive	$M = 5.0, A = 1.2$	
Re-orientation	$M = 1.5, A = 1.5$	
Inspection easy	$M = 1.5, A = 1.0$	

Tables containing values required for DFM analysis (Kamrani and Nasr 2010, p. 158)

Table 6.13 Shape complexity analysis for rotational features and C_c values [4]

		Single/primary axis		Secondary axis		Complex shape
Processes	Features	R1	R2	R3	R4	R5
Sand casting		1.0	1.2	1.3	1.8	3.2
Forging		1.0	2.1	2.3	2.6	3
Sheet metal working		*Process not used*				
Machining		1.0	1.2	2.9	5.3	6.1

Table 6.14 Shape complexity analysis for prismatic features and C_c values [4]

		Single axis		Multiple axis		Complex shape
Processes	Features	P1	P2	P3	P4	P5
Sand casting		1.1	1.2	1.4	1.8	2.6
Forging		1.0	2.2	2.2	2.3	2.7
Sheet metal working		*Process not used*				
Machining		1.0	1.3	2.6	2.6	2.8

Table 6.15 Shape complexity for flat wall features and C_c values [4]

		Single axis	Secondary features		Regular shapes	Complex shape
Processes	Features	F1	F2	F3	F4	F5
Sand casting		2.1	2.3	2.8	3.7	5.0
Forging		1.0	1.2	1.6	2.5	3.6
Sheet metal working		1.0	1.2	1.5	2.2	2.5
Machining		1.0	1.4	3.1	5.4	6.5

Tables containing values required for DFM analysis (Kamrani and Nasr 2010, p. 159)

Table 6.16 Material suitability and C_{mp} values [4]

Processes / Material	Cast iron	Aluminum alloy
Sand casting	1.0	1.0
Forging	*Process not used*	1.0
Sheet metal working	*Process not used*	1.0
Machining	1.2	1.0

Table 6.17 Waste factor analysis for rotational features and W_c values [4]

	Single/primary axis		Secondary axis		Complex shape
Processes / Features	R1	R2	R3	R4	R5
Sand casting	1.1	1.1	1.2	1.3	1.4
Forging	1.1	1.1	1.2	1.2	1.3
Sheet metal working	*Process not used*				
Machining	1.6	2.0	2.5	3.0	4.0

Table 6.18 Waste factor analysis for prismatic features and W_c values [4]

	Single/primary axis		Secondary axis		Complex shape
Processes / Features	P1	P2	P3	P4	P5
Sand casting	1.1	1.1	1.2	1.3	1.4
Forging	1.1	1.1	1.2	1.2	1.3
Sheet metal working	*Process not used*				
Machining	1.7	2.2	2.8	4.0	6.0

Table 6.19 Waste factor analysis for flat wall features and W_c values [4]

	Single/primary axis		Secondary axis		Complex shape
Processes / Features	F1	F2	F3	F4	F5
Sand casting	1.1	1.2	1.3	1.4	1.6
Forging	1.1	1.1	1.1	1.2	1.3
Sheet metal working	1.2	1.2	1.4	1.5	1.6
Machining	1.8	2.4	4.0	6.0	8.0

Selection matrix

Criteria	Number of parts	Design alterations required (Cost incurring)	Ease of manufacturig	Ease of assembly	Dismantlability	Assembly or manufacturing error correction	Mistake proofing	Automation Possibility	Ability to Sustain under operation condition	Modularity	**Total**
Current arrangement	N	N	N	N	N	N	N	N	N	N	0
Stators shrink fitted	1	1	1	1	-1	-1	-1	1	0	0	**2**
Welded plates and ring to casing and bearing plate respectively (steel to aluminum)	1	1	-1	-1	-1	-1	-1	1	0	1	-1
Adhesive bonding of rings (ring to hold sensor) and to hold the stators in place (steel)	0	1	1	0	-1	-1	-1	0	-1	1	-1
Adhesive bonding fittment of stators with mistake proofing profiles	1	-1	-1	1	-1	-1	1	-1	-1	1	-2
Adhesive bonding fittment of stators	1	1	1	1	-1	-1	-1	-1	-1	1	0
Rings welded to hold the sensor and actutor sensor (change material to aluminum) with mistake proofing profiles	1	-1	-1	-1	-1	-1	-1	1	1	1	-2
Single ring to hold sensor	1	-1	-1	1	1	0	0	0	0	0	1
Press fit	1	-1	-1	-1	-1	-1	-1	-1	0	1	-5
Thread fit	1	-1	-1	-1	1	-1	-1	-1	0	1	-3
Tolerance ring	1	0	-1	-1	-1	0	0	1	1	-1	-1
Snap rings	1	-1	-1	1	1	-1	0	-1	1	-1	-1
Stepped cylinder	1	-1	1	-1	1	0	0	0	0	-1	0
Clamps	1	1	1	1	1	-1	1	-1	1	1	**6**