An Investigation on Leakage Behaviour of Seals for Aerospace Applications

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By

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The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"An Investigation on Leakage Behaviour of Seals for Aerospace Applications"** by A. Agarwal in partial fulfillment of the requirements for the degree of **Master of Science**.

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Rotterdam, The Netherlands Ankit Agarwal
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ABSTRACT

This research, performed at Airbus Defence and Space Ground System Test Engineering department in Seville, Spain, is a part of ELDAS (Engineering for Leak Detection in Aircraft Systems) project. It deals with carrying out an investigation on the leak behaviour of the sealing systems used in an aircraft particularly A400M. The sealing integrity of a fuel system is, inarguably, a critical aspect in an aircraft sealing technology. The need for NO fluid leakage and consequently preventing any structural damage to the internal components of an aircraft drives the aircraft designers towards carrying out a detailed research on the sealing systems. The analysis is divided into two parts: firstly, to conduct a structural analysis of the current installation and to computationally study the rubber behaviour; secondly, the characterization of the leakage. This combined analysis is to investigate the current issues associated with the sealing system and propose methods for leak estimation by characterization of leak applicable to the fuel system of an aircraft. Several parameters e.g. fluid properties, material properties, surface roughness, flow conditions to name a few, are thought to be correlated with fluid leakage. This document along with the literature study report will summarize the investigation performed to study the effects of these parameters on the seal leak rate.

The structural analysis is performed using Ansys Mechanical Parametric Design Language 14.5 to verify if the current design parameters are well within the prescribed limits. The non-linear behaviour of rubber seal is studied and verified with different available analytical models. A grid independence test is performed via error analysis to further strengthen the simulation obtained results. Various time dependent rubber viscoelastic behaviour are studied to understand the seal deterioration over time. This deterioration in stress within a rubber seal (Fluorosilicone) might increase leakage potential over a period of time. Investigation is also performed to understand the importance of lubrication on sealing performance along with the adverse effects of reusing an o-ring seal multiple times and the associated leak potential. Furthermore, analysis is done for different dimensional cases considering the manufacturing tolerance values. Lastly, the complex extrusion behaviour of the seal at high fluid pressure is studied and simulated to understand the seal failure at high pressure.

During the literature review, it is observed that of all the leak estimation models available, no formulation appears to have general validity, so a more general model based on different flow regimes appears to be necessary taking into account the different fluid parameters, leak geometry and operating conditions. The study on the leak behaviour of static seals of an aircraft is performed to establish a correlation between gas and liquid leaks. This study can then be used to facilitate industrial leak testing by providing a correlation between leak rates for liquids and gases which can be used to replace liquid based testing with gas based testing. Obviously, the study can be used for planning further experimentation and validation purpose.

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1 Introduction

Sealing at the joints are widely used in pressure vessels connections and similarly in piping joints of an aircraft fuel system installation. The prediction and detection of a leakage has always been a topic of profound importance, not only for system failure but also due to economic reasons. Three important reasons behind leak investigation is a) prevention of material loss, b) prevention from contamination and c) reliability. A leak is an unwanted passage that allows fluid flow across a seal. It has been proved that when two different surfaces are pressed against each other, there still exist some defects/micro-pores between two surfaces even at high compression (Majumdar and Bhushan, 1991) resulting in small leaks. At times, improper installation or seal design aggravate this behaviour. With a view to understand the mechanisms involved in fluid flow through these defects, several leak theories have been developed and investigated. The understanding of leak in rubber elastomeric seals under loading is the subject of this study. Among various facets of rubber properties, viscoelasticity is an important aspect of O-ring seal degradation over time. The initial applied stress decays over time, roughly proportional to the logarithm of the time of contact. An O-ring, generally used to join different piping, is one of the most commonly used seal and often act as a source of leak. Even then, it finds profound application in aircraft sealing due to its light weight, low cost and easy to install (or replace) properties. In past, this resulted in catastrophic events. One prominent example is the Challenger catastrophe. Feynman explained this phenomenon in a famous experiment with O-rings in cold temperature (Feynman, 1988). Consequently, there is a need for better understanding of leaks through compressed O-rings.

The research is about investigating the structural design of the seal using various hyperelastic and viscoelastic models to simulate the sealing material behaviour under loading and its variation with time. Also, applicability of leak estimation models available in various domains e.g. cracks in thick wall, flange joints, thin wall surfaces et cetera into porous media environment e.g. O-rings is also interesting in order to establish an understanding of leaks. The project also deals with the study and understanding of a variety of fluid parameters and their interactions under the influence of applied compression, fluid pressure and temporal degeneration that might lead to leakages. The aim of the investigation is to carry out structural analysis using Ansys Mechanical to study the rubber material behaviour and also to do an analytical flow analysis for better leak rate estimation. Also, based on the study, a standard method for leak rate measurement can be proposed for leakage in the fuel system of an aircraft. The findings could lead to the formulation of a more general leak prediction model that can allow to define a semi-empirical correlation between liquid and gas leaks. Consequently, the study can form a firm foundation to plan and conduct an experimental study to provide required validation to the current analytical and simulated models.

1.1 Background: Industrial Framework:

In an aircraft, the components that contain pressurized gaseous or liquid fluids are of various sizes, complexity and application. For a better aircraft performance the aircrafts structural weight of all its components and sub-components must be made as light as possible and in this design process the tradeoff between the complexity of the components and the degree to which a joint should be free of

leakage is decided. This tradeoff is made taking into account the allowable amount of leakage for the range of operating pressure and temperature and the means by which leakage can be sensed and localized. The ELDAS (Engineering for Leak Detection in Aircraft Systems) project is an initiative project for the development of new technologies for detecting and measuring leaks in the fluid system of aircraft systems.

In the domain of aviation industry, leak detection and quantification in fluid systems – including hydraulic and pneumatic mechanical operating system are vital both for the longevity of the system themselves and also for the aircraft in general. As a matter of fact, the tests are done in different periods of the life of an aircraft, when it seems necessary to verify the leak performance of the fluid systems. In the first place, verification of the expected operation of the installed fluid systems is carried out by means of functional testing. These functional tests contain a number of procedures and methodologies that completely define the actions to be performed during the tests and to determine if the results are within the anticipated limits. It has to be kept in mind that functional tests are used not only for the verification of the tightness of the fluid systems but also defined for all systems in an aircraft such as electrical systems, power plant, avionics systems et cetera. However, these systems which are not related or do not contain fluids are beyond ELDAS project objectives.

1.2 Motivation

The leak detection and measurement falls under the category of NDT (Non Destructive Testing) and must comply with the characteristics of NDT (Patrick O. Moore, 1996). The operational reliability of an aircraft both for individual system and final assembly grows if significant consideration is given to the leakage testing. In the industrial context including the chosen field of functional testing it would be appropriate to say that the Eldas project falls under the category of research and development through which a deeper understanding about the leak quantification has to be developed for the proposed industrialization of the final assembly line of the aircraft. In addition to these, some basic reasons for structural analysis and leak characterization are:

- **Prevention of material loss** e.g. fuel or hydraulic liquids
- Prevention from **contamination,** creation of fatal situations e.g. fuel leak into the fuselage, fire due to fuel leak
- Detection of faulty systems and keep a check on the **reliability** of the system

Undoubtedly, there is a continuing need to improve the efficiency of industrial processes in each area that relate to performance, health and safety of an aircraft and also to be placed within the strict environmental emission directives that are expected to be even stricter in near future. Clearly, the Eldas project with its different lines of research, presents itself as an opportunity to guide the engineering of functional tests on the right path of industrial development.

1.3 Research objectives and scope

This study, part of Eldas project, is an initiative of research, development and innovation for the improvement of existing leak detection and quantification techniques and means of improvement and creation of new technologies in industrial operation domain. The domain of this project includes:

- Hydraulic line: establishment of new criteria of sealing with gas for hydraulic systems through formulation of correlation between leaks in joints that are obtained with corresponding hydraulic fluids and gases
- Characterization of leak based on parameters affecting leak identified during the literature study
- Structural analysis: to study the current installation and study the rubber seal degradation and its effect on leak and propose improvements
- Study o-ring extrusion behaviour computationally into the clearance gap

This thesis is based on acquiring a better understanding of the seal requirements which are preset by the fluid mechanical system designers, setting limitations and study possible improvements. In addition, it is also a part of the thesis to identify the different external operating parameters such as temperature, pressure, volume of the component, type of leakage/flow and then find the correlation among them to find out the degree to which these parameters affect leakage.

This project was born from the pursuit of setting up of standards in aircraft hydraulic systems. In particular, the study will focus on the riser (fuel refueling from bottom of the aircraft to the central fuel tank located in the high wings) of the fuel system installation of A400M, manufactured by Airbus Military.

1.4 Thesis Structure

This section outlines the remainder of the thesis. The details of the literature study can be read in the literature review report attached along with this thesis report. The review has three basic components i.e. the structural part, the leak quantification part and leak detection principles. It provides a nice overview of the leak affecting parameters and also defines the theory that can be used for leak characterization.

Chapter 2 portrays briefly the theoretical description and the jargon associated with leak of the fuel system which is an important part of thesis and the focus point of this project. This section encompasses some of the major aspects and components of leak along with the discussion on the various units used to express leak rates. Also, it talks about the sensitivity of leak test together with zero and no fuel rate concept. The section ends with a brief explanation on the parameters that affect leak rates.

Chapter 3 includes the structural analysis of the seal installation. It provides an overview of the required theoretical background, different models used, description of the problem addressed and the results and analysis sections. This approach is adapted so that the reader can connect the theory and the analysis in a simpler and better way without getting lost into theories.

Chapter 4 presents the leak flow characterization section of the thesis. The section starts with different describing different parameters affecting leak and then dividing it into different flow regimes. The plots, results and analysis part follows for each regime right after the analysis for better understanding. The chapter closes by providing the necessary correlation expressed in nomographs.

Finally in chapter 5, the conclusions of the analysis is provided with the findings of this research, theoretical contributions and recommendations for doing similar analysis. The thesis ends with discussion on the limitations of the research analysis as well as exploring avenues for the future studies.

All the necessary python codes for nomographs, FORTRAN codes for slip flow analysis, Ansys Parametric Design Language (APDL) codes for the structural analysis and Matlab codes for the turbulent choked flow analysis are attached in the appendix section. Also, the recommendations for conducting similar analysis in future and the challenges faced and solved during the analysis is provided in the appendix section.

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