Clean Sky	EUROPEAN COMMISSION RESEARCH AND INNOVATION DG HUMAN RESOURCES AND MOBILITY	Final Report

Project No: 326023

Project Acronym: SNRPBBEARING

Project Full Name: NTN-SNR Proposal for Propellers Blades Bearings Design and Manufacturing

Final Report

Period covered: from 04/02/2013 **to** 03/12/2015

Start date of project: 04/02/2013

Project coordinator name:
Mr. Guillaume LEFORT

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Project coordinator organisation name:
NTN-SNR ROULEMENTS SA

Final Report

PROJECT FINAL REPORT

Grant Agreement number:	326023
Project acronym:	SNRPBBEARING
Project title:	NTN-SNR Proposal for Propellers Blades Bearings Design and Manufacturing
Funding Scheme:	FP7-JTI-CS
Project starting date:	04/02/2013
Project end date:	03/12/2015
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Final Report

Please note that the contents of the Final Report can be found in the attachment.

4.1 Final publishable summary report

Executive Summary

The SNRPBBearing project, led by NTN-SNR, is a SAGE 2 Integrated Technology Demonstrator from the Clean Sky programme. The goal of this project is to design, manufacture and test the propeller blade bearings for the upstream and downstream propellers of SAGE 2 Open Rotor.
The Upstream Propeller module consists of 12 propeller blades and the Downstream Propeller module consists of 10 propeller blades. The propeller blades of the two rotors are attached to polygonal rings and are orientated at various angles by the two independent Pitch Control Mechanisms.
The propeller blade bearings ensure the transfer of aerodynamic and centrifugal loads to the respective polygonal rings while allowing the pitch change of the blades.
The main functions of these bearings are to:
• allow oscillatory rotation between the polygonal ring and the propeller blade shaft;
• transmit the centrifugal and aerodynamic loads from the propeller blade to the polygonal ring;
• be resistant to the environment;
• ensure the stiffness between the propeller blade root and the polygonal ring;
• resist the load caused by the loss of a propeller blade (twice the maximum centrifugal load).
The objectives of the project were to:
• design the two bearings for each propeller;
• define the mitigation plan to reach TRL5;
• complete the mitigation plan and especially the development tests;
• successfully pass the validation test;
• manufacture the bearings for the two propellers;
• deliver 26 bearings to the Topic Manager.
At the end of the project, all the objectives have been achieved. All the tests were performed successfully and the bearings were delivered to the Topic Manager.

Summary description of project context and objectives

The SAGE2 counter-rotating open rotor is the most attractive aircraft engine concept to reduce the fuel consumption and the gas emission (CO2, NOx, …). In fact, this concept allows improving the propulsive efficiency and the thermal efficiency while growing up the by-pass ratio (higher the by-pass ratio is, lower the fuel consumption is with the same weight). Moreover, this concept combines the qualities of the turboprop (propulsive efficiency, thermal efficiency) and the benefits of the turbojet engine (higher flight speed, lightness,…).

However, before introducing this concept in production, several technical issues have to be solved. A lot of innovative works have to be studied for the integration of the open rotor to the aircraft and for the propulsive part (gearbox, propeller blade design, propeller blade integration: pitch change mechanism, propellers blade bearings, bearing lubricant and bearing sealing system). The propeller blade bearings are one of the critical parts for Open Rotor Engine.

Regarding the propeller blade bearings, NTN-SNR has a very good experience in the current concepts. However, due to the SAGE2 technical specification and the location of the propellers, none of the current blade bearing designs can be used on the open rotor concept.
The four main bearings' specific requirements for this innovative application were:
- Criteria 1: High level of loads (especially centrifugal force) with +15% compared to the current application
- Criteria 2: Large temperature range and high level of maximum temperature (-55°C to 180°C): twice higher than current application
- Criteria 3: Smaller allocated room to design the solution than existing one
- Criteria 4: The sealing device has to be inserted in the new propeller blade bearing contrary to the

current design.

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Description of main S & T results/foregrounds

To meet the specification requirements, various innovative works were conducted and different solutions were studied, namely to:
A) design a new bearing architecture addressing criteria 1, 2, 3 and partially 4
B) improve the bearing material properties using new materials which address criteria 1, 2 and 3.
C) develop a new complex tribological system in order to minimise the friction torque and avoid any raceway wear (criteria 1 and 2)
D) develop an innovative sealing system answering to criteria 4.

A) Bearing architecture

Based on criteria 1 and 3, several architectures of bearings have been defined and calculated using specific new adapted Finite Element methodology.
This new methodology has been developed during the project because the constraints of integration, especially the complex thermal gradient and the stiffness of parts. Eventually, only two architectures meet the specifications and thanks to these calculations, the best bearing architecture was selected.

At the end of the first reporting period, the selected architecture and its justification was presented during the Preliminary Design Review (PDR) which was passed with success. The bearing development plan was established and thus approved by the Topic Manager.
During the second reporting period, NTN-SNR ended the design of the bearing. NTN-SNR performed a new global finite element with thermal study to validate the impact of the modifications of Topic Manager's parts on the bearing. The bearing design was frozen and the Critical Design Review was successfully passed, the drawings of the bearings were done and the manufacturing process review was issued.

B) Material studies
NTN-SNR has to improve the bearing material properties using new materials able to address criteria 1 and 3. The work was done in 3 parts.
1) Determination of mechanical characteristics of material
The mechanical characteristics (Re, Rm, KIC) have been studied for the steels M50, 32CDV13, M50NIL, 40CDMS8-4-6 and 40NCD7.
In conclusion of this study, the material characteristics allow the selection of the appropriate material for each bearing component regarding the structural aspect.

2) Study of tribological behaviour
The study of tribological behaviour of various steels (M50, 32CDV13 and M50NIL) was done regarding literature and tribometer tests.
The conclusion of this material study showed that 32CDV13 has the best tribological behaviour. This study provided evidence that having a specific tribological system is necessary in order to maintain the good behaviour during the whole life of the bearing for the entire engine mission.

3) Study on ceramic rolling element (ball and roller)
NTN-SNR studied the impact of hybrid bearing for this type of application based on literature data and NTN-SNR test data.
This study shows the following benefits compared to the steel rolling elements:
- Saving of the mass on the bearing (-1 kg / bearing on upstream propeller)
- Reduction of centrifugal load

- Better behaviour under poor lubrication
- Lower friction coefficient.

C) Tribological system selection:
It is important to highlight that the contact lubrication is a key parameter for the success of this project because both the life duration of the bearing and the bearing starting torque depend on the contact lubrication. Due to the extreme specification, the lubrication cannot be done by one type of lubricant. Therefore, NTN-SNR has developed a complex tribological system to allow for good bearing lubrication.

This selection was divided into three steps:

1) Exploration of existing solutions
The aim of this task was the exploration of all existing lubricant solutions. This task was based on NTN-SNR experiences, literature and supplier experiences. It is important to highlight that the major criterion for the lubricant is the capacity to sustain very high contact pressure (up to 4 GPa). It is also a challenge for the surface treatment.
12 potential greases and several surface treatments were studied.
Only the four best greases and the best surface treatment were further studied in the following step.

2) Tribological solution definition
The target of this step was to select the three best solutions regarding the global tribological behaviour. NTN-SNR explored the different types of lubricants (grease and surface treatment) and the combination of the different types. The impact of the bearing ring materials and their heat treatment was also evaluated. The tribological system is a complex system composed of ring and ball materials, potential roughness optimisation, surface treatment and grease. The ring and ball materials are established by the bearing sizing. Several solutions were studied for the three other components.

Firstly, many series of tests of all the identified solutions for each component which composed the tribological system were performed separately.

In fact, the solution was more complex than expected and the risk not to detect the impact of one parameter is high. So to optimise the solution and mitigate the risk, NTN-SNR and its subcontractor decided to increase the test matrix (more solution and more types of laboratories tests).
The 3 best tribological systems were selected regarding laboratory test results.

3) Validation of the selected solutions

The aim of this task was to test the three best selected solutions in representative conditions, studying the “False Brinelling Effect” on three test benches: one at room temperature, another at high temperature and the last one at low temperature. The first two test rigs already existed at NTN-SNR and the last one had to be built.
These 3 solutions were compared with the solution of reference used on the current application for the test at room and low temperature. However, the high temperature tests were performed to validate the good behaviour of the solutions at 180°C, where the reference is not valid. The main difference between them was the size of the samples. These tests performed the equivalent in service time on the three best solutions.
Conclusion: Thanks to all these tests, NTN-SNR defined and developed a customised complex tribological system which has the same performance as the propeller blade root “in service” solution in an environment respecting the requirements criteria. Moreover, the 3 best solutions do not have exactly the same behaviour and the same wear mechanism. The behaviour of the best solution is similar to the current solution used on the existing propeller bearings at low and room temperatures.

D) Sealing device

Intensive work has also been done to design complex sealing devices to avoid the leakage of lubricant outside of the bearing and the penetration of pollution inside the bearing. In fact the bearing sealing system is composed of two seals: the upper seal and the lower seal. The maximal equivalent

pressure applied on the upper seal by the centrifugation of the grease is about 16 bars with safety factor. In addition, at low temperature the grease has to have a very low viscosity to ensure a good lubrication of bearing.
The detailed study of sealing, including functional analysis, risk analysis and product Failure Mode and Effect Analysis dedicated to the sealing, was done with a NTN-SNR supplier. . Due to the specificity of the requirement and to optimise the integration aspect (torque, weight, cost …), the architecture of the lower and upper seals used on the bearing assembly is not the same. However the upper and lower seals are the same for the upstream and downstream propeller blade bearings in order to save manufacturing and development costs. The Finite Element calculations showed larger displacements of the seal seatings than the one for existing applications. Therefore, the seal design has to be reinforced to take into account these displacements.
Due to the high level of risk, a sealing validation plan was performed. It consists of six additional tests:
1) material compatibility tests:
These are laboratory tests to validate the good behaviour of the seal material with the materials (fluids or chemical components) that could be in contact with the seal during its life.
2) “Raffer test”:
This is a fatigue pressure test to study the behaviour of the seal regarding complex cycles and endurance..
3) adhesive test:
This test aims to validate the good adherence between the elastomer part of the seal and the frame. It is important to highlight that an adhesive issue could result in a non-optimised seal design which puts a high level of strain on the link between the elastomer and the frame.
In order to solve this issue, several solutions were studied, designed, manufactured and tested. The first solution consisted of the reinforced adherence solution realised by surface treatment of the frame. However, the reinforcement of adherence is an expensive solution and the manufacturing repeatability requires a considerable amount of time to inspect the part after manufacturing. That is why this solution is not the preferred solution. The second solution consisted of the modification of the shape of the seal to reduce the stresses in the failure area and solve the adhesive issue.
4) dismounting test:
This test measures the load necessary to disassemble the seal of the bearing in order to demonstrate that there is no displacement of the seal and deflector during the engine test.
5) starting torque measurement on seal:
This test aims to measure the starting torque of the seal alone. The torque value measured by this test is used to compare the starting torque of the three solutions.
6) starting torque measurement on standard representative bearing (These tests were performed on a standard representative bearing in terms of diameter, ball size and number of balls.
This test mitigates the risk of having a starting torque higher than the specification. In fact, if the bearing torque is too high, the actuator which controls and changes the blade pitch angle cannot modify the angular position of the blade. Thus the engine does not work. A specific test methodology was developed for this project.
The global starting bearing torque is not equal to the sum of all the component starting torques due to the interaction between the components. The starting torque distribution is not well known. Thus these results were extrapolated with the starting torque results on seal alone.

The best seal design regarding life duration was assembled on the bearing prototypes.

After the completion of the four innovative works, the bearings were manufactured. After that, the prototype bearings were validated:
- for criteria 1, 2 (partially) and 3, the good behaviour of the bearing under load was validated with tests on ball bearing on a compression/torsion test machine. The two bearings successfully passed the limit and ultimate load tests. And the torque under load is two times lower than the Topic Manager’s torque requirements included in the course of the project. The two bearings will allow:
o good behaviour of the engine, allowing oscillatory rotation between the polygonal ring and the propeller blade shaft, transmitting centrifugal and aerodynamic loads from the propeller blade to the polygonal ring, ensuring the stiffness between the propeller blade root and the polygonal ring
o safe working of the engine, avoiding the loss of propeller blade.
The results of these representative tests were compared with the starting tests done on the prototype bearing. These two tests used the same level of starting torque, around 50Nm.

- For criteria 4, due to the lack of test bench availability, the relevant sealing test was not performed on the whole prototype. This criterion is only validated by the “Raffer” tests performed on the seals. The project developed and thoroughly tested the bearing prototypes up to TRL5. As a result, 26 bearings for the two SAGE 2 demonstrator propellers with the substantiation documents have been delivered to the Topic Manager.

In conclusion, NTN-SNR has developed during this project:
- a new compact self-lubricated architecture of bearing
- a new complex tribological system to allow a good lubrication of bearing under extreme conditions (centrifugation loads and high temperatures)
- a new sealing device compliant with high fatigue safety margin.

All these innovations will be definitely validated on SAGE 2 ground test demonstrator, especially for the vibration and life duration of the bearing.

Potential impact and main dissemination activities and exploitation results

The bearing solution developed in the frame of this project by NTN-SNR will now become the technical standard for all the blade root applications (unducted or ducted propeller) which work in high speed conditions and high temperature environments, in a small allocated room where sealing and self-lubricant are requested.
a) potential impact and exploitation results
- environmental impact
For the aerospace industry: these propeller blade bearings are one of the critical Open Rotor Architecture parts. Without efficient, reliable and safe propeller blade bearings, no Open Rotor Engine could be introduced into mass production for commercial civil aircraft. In fact, the failure of the propeller blade bearing leads to an engine stop or engine failure.
The impact of the new technologies developed for these bearings could be applied to several aerospace applications, such as propeller blade bearings, fan blade bearings, main rotor blade bearings, swash plate, etc.
This innovation can also benefit other industries, namely railway and automotive. The tribological system allows for the reduction of the bearing torque, thus reducing fuel consumption for car application, especially wheel bearing. The benefit evaluation for automotive wheel bearing application will be done in 2016.
Four patents were filed based on the results of these studies.
b) Dissemination activities
Several meetings and exhibitions of bearings were organised by NTN-SNR R&D team for the employees of the companies of NTN Corporation.
One article was published in ‘The Engineer’ magazine, number 160 (February 2016):
http://www.theengineer.co.uk/bearings-for-open-rotor-aero-engines/.
This project was a nominee for the Clean Sky Best Project Award, and exhibited one poster at the Clean Sky General Forum on the 4th April 2016 in Brussels.
One article was published on Aerobuzz website (April 2016):
http://www.aerobuzz.fr/defense/article/ntn-snr-en-pointe-sur-les-nouveaux
One article will be published in ‘Air & Cosmos’ magazine (April 2016).

Further communication:
In the second step, when all patents have been granted and tests on Ground Test Demonstrator have been performed, NTN-SNR will communicate on the results obtained on the technology developed for this project in scientific publications or scientific conferences.

Address of project public website and relevant contact details

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4.2 Use and dissemination of foreground

Section A (public)

Publications

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Is open access provided to this publication ?	Type

LIST OF DISSEMINATION ACTIVITIES								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed

Section B (Confidential or public: confidential information marked clearly)

LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS,UTILITY MODELS, ETC.					
Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)
Patents	Yes		FR1559612	Roulement de pied de pale	NTN-SNR Roulements
Patents	Yes		FR1561471	Roulement pied de pale et son procédé de fabrication	NTN-SNR Roulements
Patents	Yes		FR1561478	Cage percee pour montage	NTN-SNR Roulements
Patents	Yes		FR1562656	Tribologie roulement pied de p ale	NTN-SNR Roulements

OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND								
Type of Exploitable Foreground	Description of Exploitable Foreground	Confidential	Foreseen embargo date dd/mm/yyyy	Exploitable product(s) or measure(s)	Sector(s) of application	Timetable for commercial use or any other use	Patents or other IPR exploitation (licences)	Owner and Other Beneficiary(s) involved

ADDITIONAL TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND	
Description of Exploitable Foreground	Explain of the Exploitable Foreground

4.3 Report on societal implications

B. Ethics

1. Did your project undergo an Ethics Review (and/or Screening)?	No
If Yes: have you described the progress of compliance with the relevant Ethics Review/Screening Requirements in the frame of the periodic/final reports?	

2. Please indicate whether your project involved any of the following issues :

RESEARCH ON HUMANS

Did the project involve children?	No
Did the project involve patients?	No
Did the project involve persons not able to consent?	No
Did the project involve adult healthy volunteers?	No
Did the project involve Human genetic material?	No
Did the project involve Human biological samples?	No
Did the project involve Human data collection?	No

RESEARCH ON HUMAN EMBRYO/FOETUS

Did the project involve Human Embryos?	No
Did the project involve Human Foetal Tissue / Cells?	No
Did the project involve Human Embryonic Stem Cells (hESCs)?	No
Did the project on human Embryonic Stem Cells involve cells in culture?	No
Did the project on human Embryonic Stem Cells involve the derivation of cells from Embryos?	No

PRIVACY

Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)?	No
Did the project involve tracking the location or observation of people?	No

RESEARCH ON ANIMALS

Did the project involve research on animals?	No
Were those animals transgenic small laboratory animals?	No
Were those animals transgenic farm animals?	No
Were those animals cloned farm animals?	No
Were those animals non-human primates?	No

RESEARCH INVOLVING DEVELOPING COUNTRIES

Did the project involve the use of local resources (genetic, animal, plant etc)?	No
Was the project of benefit to local community (capacity building, access to healthcare, education etc)?	No

DUAL USE

Research having direct military use	No
Research having potential for terrorist abuse	No

C. Workforce Statistics

3. Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	Number of Women	Number of Men
Scientific Coordinator	3	4
Work package leaders	1	3
Experienced researchers (i.e. PhD holders)	3	0
PhD student	0	0
Other	0	0

4. How many additional researchers (in companies and universities) were recruited specifically for this project?	0
Of which, indicate the number of men:	0

D. Gender Aspects

5. Did you carry out specific Gender Equality Actions under the project ?	No

6. Which of the following actions did you carry out and how effective were they?	
Design and implement an equal opportunity policy	Not Applicable
Set targets to achieve a gender balance in the workforce	Not Applicable
Organise conferences and workshops on gender	Not Applicable
Actions to improve work-life balance	Not Applicable
Other:	

7. Was there a gender dimension associated with the research content - i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?	No
If yes, please specify:	

E. Synergies with Science Education

8. Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?	No
If yes, please specify:	

9. Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?	No
If yes, please specify:	

F. Interdisciplinarity

10. Which disciplines (see list below) are involved in your project?	
Main discipline:	
Associated discipline:	1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)
Associated discipline:	1.3 Chemical sciences (chemistry, other allied subjects)

G. Engaging with Civil society and policy makers

11a. Did your project engage with societal actors beyond the research community? (if 'No', go to Question 14)	No
11b. If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?	
11c. In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	
12. Did you engage with government / public bodies or policy makers (including international organisations)	
13a. Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?	

H. Use and dissemination

14. How many Articles were published/accepted for publication in peer-reviewed journals?	0
To how many of these is open access provided?	0
How many of these are published in open access journals?	0
How many of these are published in open repositories?	0
To how many of these is open access not provided?	0
Please check all applicable reasons for not providing open access:	
publisher's licensing agreement would not permit publishing in a repository	No
no suitable repository available	No
no suitable open access journal available	No
no funds available to publish in an open access journal	No
lack of time and resources	No
lack of information on open access	No
If other - please specify	
15. How many new patent applications ('priority filings') have been made? ("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).	4

16. Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	
Trademark	0
Registered design	0
Other	0

17. How many spin-off companies were created / are planned as a direct result of the project?	0
Indicate the approximate number of additional jobs in these companies:	0

18. Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:	Difficult to estimate / not possible to quantify, None of the above / not relevant to the project

19. For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (FTE = one person working fulltime for a year) jobs:	0Difficult to estimate / not possible to quantify

I. Media and Communication to the general public

20. As part of the project, were any of the beneficiaries professionals in communication or media relations?	No

21. As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?	No

22. Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?	
Press Release	Yes
Media briefing	No
TV coverage / report	No
Radio coverage / report	No
Brochures /posters / flyers	Yes
DVD /Film /Multimedia	No
Coverage in specialist press	No
Coverage in general (non-specialist) press	No
Coverage in national press	No
Coverage in international press	No
Website for the general public / internet	No

Event targeting general public (festival, conference, exhibition, science café)	No

23. In which languages are the information products for the general public produced?	
Language of the coordinator	Yes
Other language(s)	No
English	Yes

Attachments	pictures_for_publishable_report.pdf
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Name of the scientific representative of the project's coordinator and organisation:	Mr. Guillaume LEFORT NTN-SNR ROULEMENTS SA
Name	
Date	02/05/2016
Signature	