Space Mechanisms and Tribology for the Joints of the European Robot Arm (ERA)

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1. ABSTRACT

The ERA program will result in a space robotic arm that interfaces with the Russian Segment of the International Space Station Alpha. This robotic arm will, in the first place, support the Cosmonauts building the Russian segment. After completion of the ISSA/RS, ERA will support the Cosmonauts by inspection and replacing in Orbit Replaceable Units (ORU' s). ERA will be launched mounted to the Scientific Power Platform (SPP) which is part of the Russian Segment. The SPP will be launched with the Shuttle.

The current launch date in the year 2001. The ERA arm basically consists of 2 limbs, 7 joints which provide the means for actuation, 1 central computer (ECC) and two end effectors.

The ERA program is an ESA project, SABCA has developed the Manipulator Joints Subsystem (MJS) of ERA.

2. MJS GENERAL DESCRIPTION

The ERA MJS consists of three assemblies, 2 wrists and 1 elbow ; each wrist assembly consist of 1 pitch joint, 1 Yaw joint, 1 Roll joint and an electronic box ; the elbow assembly consists of 1 pitch joint and an electronic box.

Figure 1: Elbow Assembly

Figure 2: Wrist Assembly

3. MJS DESIGN CONSTRAINTS

The main design constraints of ERA are listed hereunder :

- During launch, the total ERA mass will be less than 650 Kg approx ; the MJS joints represent 57% of this budget ;
- Control performances :
  The joints must enable the arm to achieve its performances in tracking and proximity control; the joint controller is implemented in a dedicated software, which is maintainable in-orbit ;
- Lifetime :
  The expected lifetime of ERA in-orbit is 10 years ;
- Reliability and safety
- Environmental constraints : vibrations during launch, thermal vacuum (between –55°C and +90°C), LEO environment (micrometeoroids and debris, ATOX, radiations).

4. JOINT MECHANISM

Each MJS joint includes :

- A brusless DC motor,
- A resolver (velocity measurement and motor commutation),
- A high-precision joint position sensor, to feedback the joint position to the joint control electronics,
- A four-stages planetary gearbox (ratio = 454), for torque capability and speed reduction,
- A friction brake,
- An EVA shaft for manual override, in case of loss of electrical power,
- A cables harness, including power, data and video lines,
- Joint thermal control (heaters),
- Position limit switches.

a) Motor :
The motor is based upon a permanent magnet synchronous motor, and has a two-phase redundant winding.

The motor drive electronics is adjusted in such a way that the motor provides a ripple-free torque.

b) Brake :
The brake torque is provided by the contact of two smooth friction surfaces, with a chromium oxyde coating, providing excellent resistance to sliding wear and abrasion.

The brake discs are automatically applied (by 8 springs) when the brake coils are not powered; at power on, the electromagnet disengages the brake. Additionally, a microswitch position sensor provides the brake information to the joint electronics.

The challenge of the brake was to achieve a stable brake torque range, given the wide temperature and operational ranges. At discs level, the brake torque is between 0,7 and 1,1 Nm ; at joint level, the brake torque range is between 350 and 750Nm, in all static and dynamic brake operations. The stopping distance at the extremity of ERA will be 15 cm approx.

c) Gears :
The gears are made of nitrided steel, the teeth surfaces are lead ion-plated. Gears are lubricated by Braycote 601 grease. The precision gearbox provides low backlash and low frictions ; the gearbox is designed to provide torsional stiffness, also required for the overall arm control performances ; on the other hand, the planetary gears provide some bending flexibility, to allow housing distorsions due to external mechanical loads, as well as proper load distribution among the planetwheels (floating concept).

d) Bearings :
The joint rotor is supported by two main bearings ; these bearings are of double-row type and hard-preloaded, they are made of 440C stainless steel, and lubricated by Braycote 601 grease.

e) Cables :
Inside each pitch-type joint, ribbon cables are used, sliding along each other ; the cables are grouped into Teflon jackets.

For proper behavior during dynamic solicitations (vibrations) and in electro-magnetic environment, all cables are properly guided, secured by cables clamps, and shielded, as well as the connectors. Power cables are separated from video /data cables for EMC reasons).

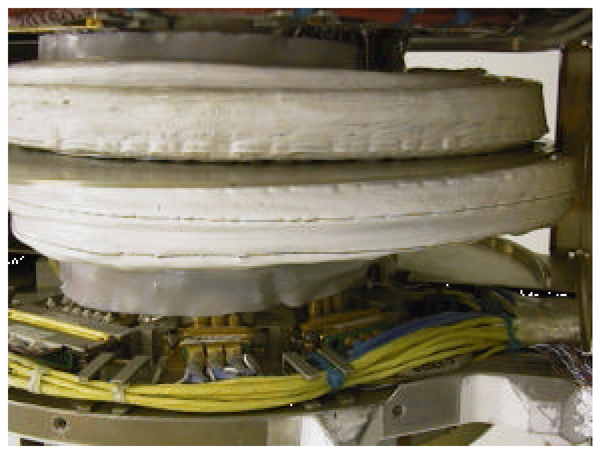

Figure 3: Ribbon Cables in Pitch-Type Joint

5. ERA TRIBOLOGY WORKING GROUP

During the earliest phase of the project (ERA Part 1), trade-off analyses were made in collaboration with E.S.T.L.,European Space Tribology Laboratory of ESA, located in the area of Manchester, U-K.

a) Gear material :
The selection of a gear material was a challenge, due to the conflicting nature of the ERA requirements : corrosion resistance, lifetime, mechanical strength, volume and mass.

SABCA performed breadboard tests with :

- Three-stage planetary gears made of maraging stainless steel MARVAL X 12, similar with CUSTOM 455 (used on Canadian Arm).
- Spur gears, made of MARVAL X 12.

Finally, nitrided steel was selected as the baseline gear material for the ERA joints, since it provides :

- High allowable hertzian and bending stresses capability (so, volume and mass could be reduced),
- High surface hardness, reducing wear effects and increasing the mechanical efficiency (so, reducing the motor size).

To avoid corrosion of nitrided steel, precautions are taken, wrt handling and storage conditions.

b) Lubricant :

A combination of Braycote 601 grease + dry lubricant was selected as the baseline for the gears of the ERA joints. The grease also provides some protection against corrosion.

The gear teeth surfaces are lead ion-plated (dry lubricant). To prevent the migration of grease, an anti-creep barrier (Fluorad) is used.

Remark : the use of dry lubricant alone was considered as risky.

c) Planetary Gear/Harmonic Drive :

Planetary gears :

- Advantages : high efficiency, low wear, long lifetime.
- Drawbacks : backlash, lower stiffness than harmonic drive.

Harmonic drive :

- Advantages : no backlash, higher stiffness than planetary gear.
- Drawbacks : efficiency dependant on thermal environment, wear, unknown behaviour of dry lubricant, reduced lifetime.

The planetary gear concept was selected as the baseline for the ERA joints, in order to meet the lifetime and environmental requirements.

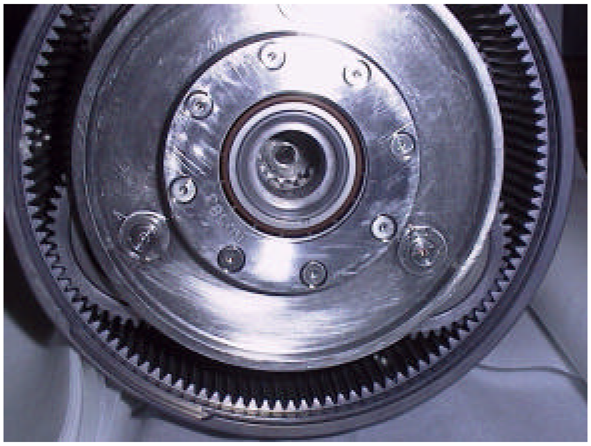

Figure 4: Planetary Gear of ERA Joint

Despite the backlash and relatively "low" stiffness of the gearbox, the Era control requirements can also be met, by adequate joint controller design.

6. JOINT CONTROL CONCEPT

The MJS receives from the ERA Central Computer (ECC) the joint position setpoint and the controller gains.

The joint controller generates the current (torque) setpoint, to be used by the motor drive electronics, as well as the motor velocity setpoint.

The joint controller uses the difference between the position setpoint and the joint position measurement, which is provided by the high precision/resolution (18bits) optical Joint Position Sensor (J.P.S.) ; it is also uses the difference between the velocity setpoint and the motor velocity which is derivated from the motor position measurement, provided by the joint resolver combined with a Resolver to Digital Converter (RDC).

The servo control algorithm is a classic linear PID implemented in the maintainable software.

7. JOINT PERFORMANCES

- Available output torque at minimum speed : 550Nm average,
- Available output torque at maximum speed : 180Nm average,
- Minimum controllable joint speed : 4,5 10^{-5} rad/sec,
- Maximum controllable joint speed : 0,05 rad/sec,
- Brake torque : 550Nm average,
- Power consumption : 165 watts (6 joints running simultaneously at 70Nm, min speed),
- Joint backlash (at 18 Nm) : 3 arc min average,
- Joint stiffness :
  - 110 000 Nm/ rad average for pitch-type
  - 160 000 Nm/ rad average for roll-type.
- Mechanical efficiency at full torque : higher than 90% in the full thermal operational range(-40°C, +75°C),
- Pitch joint operational range : +/- 120°C,
- Yaw joint operational range : +/- 120°C,
- Roll joint operational range : +/- 185°C,
- Elbow joint operational range : +30°/-176°,
- Static accuracy : 800 micro-radian,
- Tracking error at highvelocity : 3,4 mrad.

8. MASS BUDGET

The mass of the ERA joints is :

- Pitch joint : 37 kg,
- Yaw joint : 36 kg,
- Roll joint : 38 kg,
- Elbow joint and brackets : 43 kg,
- Elbow electronic box : 24 kg,
- Wrist electronic box : 33 kg.

Total MJS (2 wrists + 1 elbow) : 355 kg.

9. LIFE TESTS IN VACUUM

The Pitch of Wrist 2 was tested at SABCA facilities, in the thermal vacuum chamber.
The achieved vacuum is 10^{-6} to 10^{-7} mbar. The temperature ranged from –55°C to +90°C, which includes the qualification margins.

The following duty cycles were performed :

a) Rotation, 350Nm, 12.5 mrad/sec, 198 hours,
b) Rotation, 110Nm, 50 mrad/sec, 148.6 hours,
c) 786 dynamic braking operations,
d) 200 brake slipping operations on 3 degrees,
e) 9464 brake engagement/release operations,
f) 5945 static brake torque measurements,
g) 229 limit switches activations,
h) 62 hardstops sollicitations.

For rotation duty cycles (a and b hereabove), the tests demonstrated at least twice the specified lifetime (1000 hours, low speeds).

In order to reduce the test duration, increased speed and torque values were used, higher than those specified.

Figure 5: Thermal Vacuum Chamber at SABCA Brussels Facilities

The roll joint of Wrist 1 and Wrist 2 have seen cable life tests in order to demonstrate the operating capability of the Roll internal cable harness.

The tests were performed at SABCA facilities at ambient conditions and with joint velocity of 50mrad/sec.

The following cycles were executed :

- Roll 1 : 2000 cycles were performed,
- Roll 2 : 260 Cycles were performed

1 cycle = 720° (2 * 360°).

After the tests no cables harness damage or functional degradation was observed.

10. SAFETY/RELIABILITY

The following data are monitored :

- Joint position (optical encoder) ; each joint includes position limit switches, to prevent any motion outside the operational range,
- Joint velocity (resolver) ; any velocity above the allowed speed limit would trigger the safety barrier,
- Motor current (torque) ; any over-torque would trigger off the MJS,
- Motor temperature ; in case of overheating, the drive electronics would trigger off the MJS,
- Electronics temperature.

High-reliable EEE (Electronics/Electrical) parts are used.

11. ENVIRONMENTAL CONSTRAINTS

The MJS joints and electronic boxes are designed to survive the vibrations and shocks during launch, as well as the orbital environment, in particular, the vacuum, the wide thermal range of ISS, the micrometeoroids and debris, the Atomic oxygen (ATOX), the radiations.

The parts which are sensitive to M/D impacts are the Printed Circuit Boards (PCBs), the cable harness, the Joint Position Sensor (JPS), the heaters and sensors. The aluminium structural parts and the equivalent thickness of MLI provide the appropriate protection against the micrometeoroids and debris.

When orbiting around the earth, the ERA MJS will be submitted to an incident flux of ATOX that might result in material degradation (erosion change of thermo-optical properties, surface conductivity). The aluminum alloys and the external layer,of the MLI, made of Beta-Cloth (Fiber-Glass material), provide the protection against ATOX.

When orbiting around the earth, the ERA MJS will be submitted to radiative environment composed of charged particles from magnetospheric and cosmic origin ; this radiative environment could result in degradation of electronic components. The aluminum wall thickness provides the appropriate protection against the radiations ; radiation tolerant components have been selected.

Single Event Upsets (SEU) could mainly occur in the Joint Position sensor and in the joint controller DPRAM memory, however with a very low rate (less than 1 upset/8days) ; these SEUs are detected by the

MJS Software (which performs a SEU-check routine), moreover, the MJS safety barriers will prevent any undesirable movement. It is recommended to avoid using the ERA MJS during expected solar flares, when the SEU rates are then increased by a factor 5000 average. The MJS design is latch-up free.

12. THERMAL CONTROL

The MJS electronic boxes and joints are equipped with MLI blankets and/or white painted, for proper thermal control.

In operational mode, the heat is dissipated by an appropriate conductive thermal network ; the side panels of the electronic boxes are equipped with OSRs (Optical Sun Reflectors) for heat rejection by radiation. In any case, the joints temperature will not exceed 75°C.

In hibernation mode, the temperature of the joints and electronic boxes is kept above –35°C, by means of thermostats and heaters. The hibernation thermal power will be 69 watts approx.

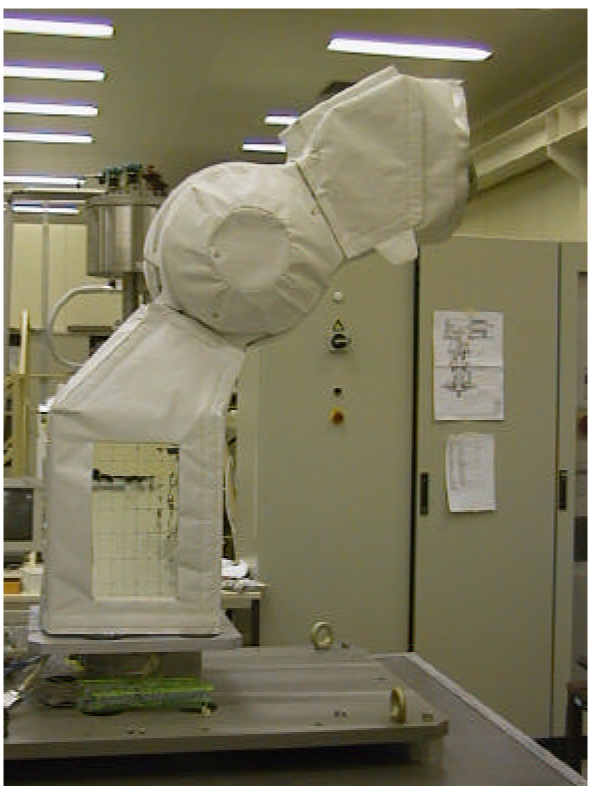

Figure 6: Elbow Assembly with MLI Blankets

Figure 7: Wrist Assembly with MLI Thermal Blankets

13. HUMAN EVA FACTORS

The ERA MJS design includes EVA manual overrides (on each joint), handrails, bevelled edges, chamfers, rounded corners on exposed surfaces, as well as angular position marking, in order to fulfill the EVA requirements.

The EVA torque to be exerted by the astronaut to rotate a joint will be around 1 - 2 Nm.

On the roll joint, a bevel gear is used, in such a way that the EVA access is perpendicular with the roll joint axis ; in nominal mode, the EVA access is discoupled from the planetary gearbox, to reduce frictions and wear of bevel gear in nominal mode ; in EVA manual override mode, the EVA access is manually engaged and latched by a specific latch-up mechanism. The effort to be exerted by the astronaut to engage/disengage the EVA access will be 88N (worst case).

14. PROGRAMME STATUS

The ERA Engineering and Qualification Model (EQM) has been assembled early 1999.

Figure 8: ERA EQM in Straight Configuration (by Courtesy of Fokker Space)

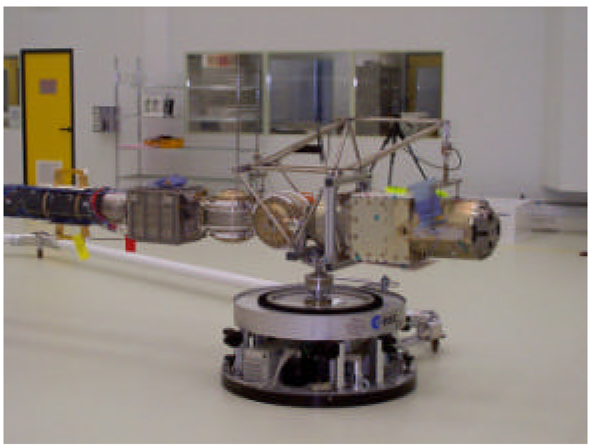

Figure 9: MJS Wrist integrated in ERA EQM for Flat-Floor Test (by Courtesy of Fokker Space)

The MJS joints have successfully passed their thermal and structural qualification tests campaign.

The flight model joints production has started, and is expected to be completed during the year 2000.

15. CONCLUSION

The real challenge of the ERA joints is to meet their complete set of requested performances during 10 years in-orbit, in particular the control performances (static accuracy, tracking accuracy), low mass, low power budget.

16. REFERENCES

a) ERA Tests results : by MM. Hofkamp (FOKKER SPACE), Shawer (DASA), Verhoeven (SABCA), Verzijden (FOKKER SPACE), presented during ASTRA Workshop (ESA : 01/02/03-12-98).

b) ERA Control Performances : by MM. Kouwen, Schulten, Visser, Stevense (FOKKER SPACE), F. De Coster (SABCA), presented during ASTRA workshop (ESA : 01/02/03-12-98).

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