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Harmonic Drive Gear Failures in Industrial Robots Applications: An Overview

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ABSTRACT

In the past years, the increment of the level of automation has been mainly dictated by the rising popularity of collaborative robots (cobots). Since these manipulators are able to share their workspace with the human operator, their failure could not only cause unexpected downtimes and economical losses, but also jeopardize the safety of the personnel working in close proximity with them. Therefore, Prognostics and Health Management (PHM) techniques could be used to optimize the robot maintenance scheduling and to prevent undesired events and unanticipated failures.

The present work provides an overview of the failure modes in harmonic drives, largely used in robotics to convey the motion of the electric motor to the joint axis, and their impact on the robot availability and reliability using Failure Modes Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA). The root causes of such degradations are investigated to provide a clear understanding of the fault to failure evolution mechanism. The paper also introduces a high-fidelity model of the gearbox which will be used to simulate the most common faults and failures in harmonic drive gears for both diagnostics and prognostics purposes.

1. INTRODUCTION

Robots have been primarily developed to automate repetitive and simple processes. Their main application is within assembly lines, where each task depends on the previous one. As a direct consequence, a sufficiently developed fault in one robot can affect the entire production line, leading to loss of quality, unexpected downtimes, and economical losses. A possible solution sees the adoption of preventive measures like planned maintenance. However, since each robot performs a specific task, it degrades at a different rate from another one, so Planned Preventive Maintenance (PPM) should be replaced with Condition Based Maintenance (CBM) for a more efficient and cost-effective approach. In addition, stand-by working stations or additional manipulators, installed inside the work cell, can be also implemented to ensure line availability. This comes with an obvious economic disadvantage since the backup robots are not used unless a failure occurs. Moreover, each robot often mounts a specific tool. In the case of malfunction, it is necessary to properly equip the backup manipulator and perform a new calibration of the entire system. A different solution would be to adopt fault-tolerant control algorithms (Abdi, Nahavandi, Frayman & Maciejewski, 2011). This would require modifying the robot joints trajectories, which is not always an option given the narrow environment in which the machine operates. Besides, this is usually achieved by adopting manipulators with kinematic redundancies, such as seven or more degrees of freedom, while most industrial robots have six.

In the past years, collaborative robotics made it possible for small-medium enterprises to approach industrial automation (International Federation of Robotics, 2017). The presence of a shared workplace between the human operator and the machine demands the fulfillment of specific norms. To do so, a cobot is driven by control algorithms able to stop its movements in case of a deviation from the programmed path. However, as highlighted by Hornung, Urbanek, Klodmann, Osendorfer, and Van Der Smagt (2014), these reactive measures could intervene when the operator's safety has already been compromised. On the other hand, a proactive approach is provided by collision avoidance algorithms (Mauro, Scimmi & Pastorelli, 2018; Scimmi, Melchiorre, Mauro & Pastorelli, 2019). Still, they could not be effective in case of degraded operating conditions of the robot arm. A cobot is labeled as safe as long as it works in nominal conditions, but this cannot be guaranteed if a fault occurs. Within this framework, PHM techniques are perceived as a breakthrough technology which can greatly increase the availability of the robot and represent an added value not only for the reduction of downtimes and economical losses, but also for guaranteeing the operators' safety. By detecting a robot fault at its early stage, it would be possible to track the degradation growth and program the replacement of the faulty machine before the occurrence of any dangerous behavior. In order to detect anomalies, Data-Driven Models (DDMs) are used to extract Health Indicators (HIs) from the manipulator. Nevertheless, a robot Mean Time Between Failures (MTBF) is in the order of tens of thousands of hours (Majid & Fudzin, 2017). This causes a lack of data coming from faulty units (Qiao & Weiss, 2017), which negatively affects the performance of DDMs.

A possible solution to the problem comes from the definition of a high-fidelity model, or digital twin, of the system. Simulated faults introduced inside the model of the robot arm would generate signals of different degraded behaviors that would be fed to DDMs to perform the features selection process. This methodology has been already validated not only for robot applications (Grosso, De Martin, Jacazio & Sorli, 2020), but also in the aeronautic field (Autin, Socheleau, Dellacasa, De Martin, Jacazio & Vachtsevanos, 2018; De Martin, Jacazio & Vachtsevanos, 2017; Nesci, De Martin, Jacazio & Sorli, 2020). To do so, it is crucial to have a clear insight into the failure modes affecting industrial manipulators and their impact on the entire system. A robot malfunctioning could be related to several causes, such as damages to its control unit, the user interface, or, more likely, to the robot joints (Zhou, Wang & Jianming, 2019). Because of any of these undesired events, the machine could operate in non-nominal conditions, or even completely stop functioning. Depending on the tasks they have been designed for, industrial robots adopt different technologies and configurations. However, a joint usually consists of five main components: electronics, sensors, motor, gearbox, and bearings. The insurgence of a certain number of failure modes affecting the first three items is likely to be autonomously detected by the built-in control logic. On the other hand, the same is not valid for the mechanical ones. The presence of wear in bearings, for example, would increase joint friction which the robot control algorithm autonomously compensates by providing slightly higher motor currents. In so doing, the correct execution of the task would be assured, but the machine would keep working in degraded operating conditions representing a possible hazard.

A critical element of the joints often overlooked by the Health Monitoring (HM) algorithms is the harmonic drive, which is often used in robotics due to its compact and lightweight design and the high reduction ratio. Due to its key role in the correct functioning of the robot, even a slight degradation of its performances could jeopardize the execution of the task for which the robot has been programmed. Nevertheless, to the best of the authors' knowledge, the literature lacks a comprehensive analysis of the failure modes of this component. To overcome this issue, they are presented in this study, with a particular focus on their effects on the behavior of an industrial manipulator. Such choice was driven by the fact that this work is part of a larger research project devoted to the definition of a high-fidelity model of the UR5 collaborative robot from Universal Robots depicted in Figure 1.

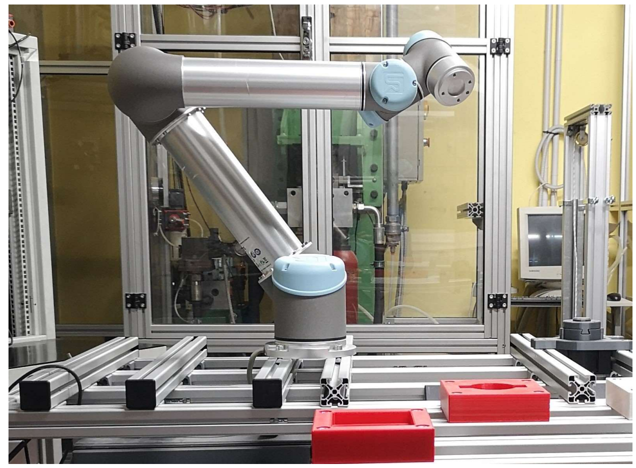

Figure 1. UR5 collaborative robot.

Despite the specific case study, the following analysis has a general validity, and it can be applied to harmonic drives in different fields and applications.

Moreover, a clear understanding of the fault to failure evolution mechanisms in this component is crucial to properly design a model of the gearbox through which to investigate the impacts of several simulated degradations on the robot behavior. This knowledge is also used to have a first insight on the effects of faults of different origin and magnitude and to avoid simulating anomalies which can only be detected by additional sensors mounted on the manipulator. This is done not to limit the movements of the robots, which are often required to operate in narrow environments, and to reduce the costs related to the implementation of PHM techniques in the industry. Even though this approach could limit the effectiveness of PHM algorithms, extracting robot health features only from the data directly available from the robot signals (i.e., joints angular positions and velocities and the motor currents) leads to the possibility of applying PHM techniques to a larger number of industrial manipulators.

2. Impact of a Harmonic Drive Fault on Industrial Robots

Since a robot usually consists of several sub-systems, a malfunctioning could be caused by single events or their combination. In this section, the impact of a Harmonic Drive (HD) fault on the availability and reliability of the industrial manipulator is highlighted. So, in the FTA diagram reported in Figure 2, only the branch related to the gearbox will be discussed, while the other ones, represented with diamonds, have been left undeveloped.

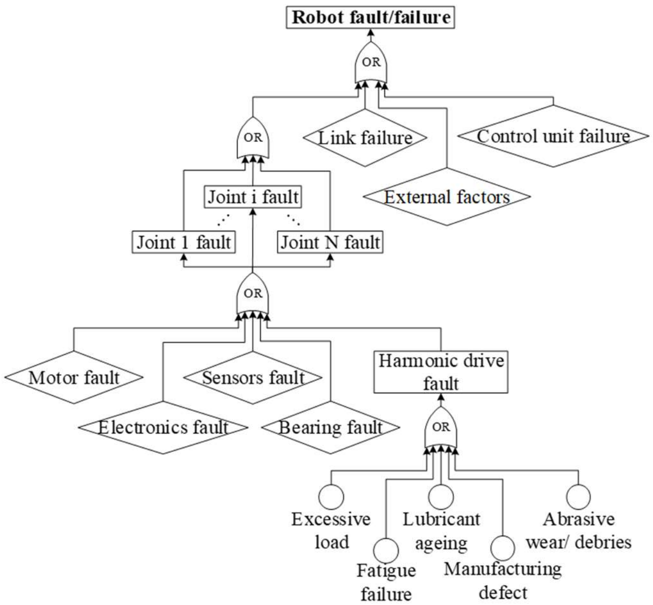

Figure 2. Robot arm fault tree analysis.

Such a deductive top-down approach is based on a tree-structure which relates, through logic gates, the Top Level Event (TLE) with the intermediate (rectangles) and the basic ones (circles). The aim is to identify the minimal combination of components faults or failures (cut sets) that can lead to a degradation of the robot performance. Thus, if a branch contains few events or elements with a high failure rate, this could result in an unreliable system. A more detailed overview about the state-of-the-art in FTA and how it works is provided by Ruijters and Stoelinga (2015).

External factors like collisions, human errors, and accidental damages are not considered critical for the correct functioning of the robot since they could be easily avoided through a correct installation and usage of the machine. Moreover, empirical experience suggests that link breakage and control unit failures are not common events. So, they are not as relevant as a damage to one of the robot joints, which is more likely to happen due to their high complexity and load history. Since each of them has a key role in the manipulator motion, a single malfunctioning could comprise the entire task. For this reason, they are all connected through an OR gate. The same logic applies to describe the interactions among the joint sub-components and their possible failure modes, with a particular focus on the HD ones.

This analysis shows how even a single fault on one gearbox in one joint of the robot arm could jeopardize the entire application. It is then necessary to have a clear insight on the root causes of such undesired events and to study the fault to failure mechanisms in these components.

Other examples of fault tree analyses for robotics applications can be found in Ferguson and Lu (2017) and in Walker and Cavallaro (1996).

3. Harmonic Drive

Harmonic drives are primarily used in applications that require lightweight and compact solutions. They can be found in the aerospace industry or inside industrial and collaborative robot arms. The working principle is based on the interaction of the three main components reported in Figure 3.

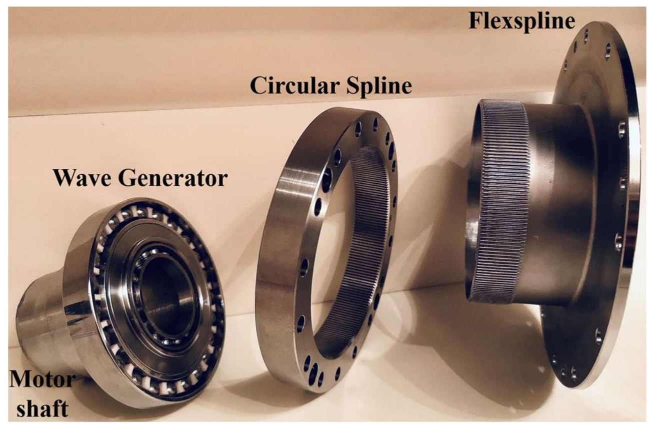

Figure 3. Main components of a harmonic drive gear.

The Wave Generator (WG) is an elliptical thin-raced ball bearing mounted on the motor shaft. Once inserted inside the Flexspline (FS), a flexible cylindrical cup with external teeth, it is used to generate an elastic radial deformation which allows the engagement with the Circular Spline (CS). In contrast with standard gears, the meshing zone is located along the two regions close to the WG major axis. This property allows about 20-30% of the teeth to be continuously in contact (Routh, 2018), leading to ideally zero backlash, high position accuracy, and repeatability. This is achieved by the adoption of a double-arc tooth profile (Chen, Li & Liu, 2019; Wu & Peng, 2015), reported in Figure 4.

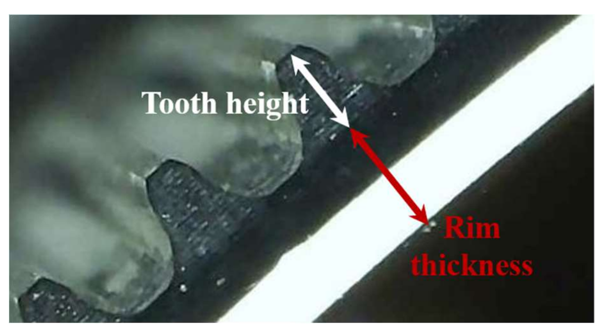

Figure 4. Double-arc profile of the flexspline tooth.

Normally, the FS has two teeth less than the CS. Due to this configuration, the output shaft moves of two teeth each full rotation of the WG, leading to a reduction ratio τ defined as:

$$\tau = \frac{Z_{FS}}{Z_{FS} - Z_{CS}} \tag{1}$$

where Z_{FS} and Z_{CS} are the number of teeth of the flexspline and the circular spline, respectively.

4. Fault to Failure Processes in Harmonic Drives

Despite its simple design, the complex working principle behind a harmonic drive leads to a high variety of failure modes that will be analyzed in this and the next sections. To properly simulate the fault nucleation and propagation mechanism which leads to a failure, it is crucial to deeply understand which components are more likely to fail and why.

4.1. Wave Generator

Besides being one of the key elements of the gearbox, the elliptical ball bearing also has a primary role in its operating life. According to Schäfer (2005), the HD end of life is reached at the beginning of pitting in the inner race of the WG. On the contrary, the outer race only breaks under excessive loads. However, as reported in section 4.5, this last scenario is more critical for leading to a failure of the HD because of ratcheting and buckling of the FS. A possible way to detect wear inside a bearing would be to analyze vibration signals coming from the robot joint.

Efficiency is also compromised by wear at the WG-FS interface. This phenomenon is particularly critical in HDs for space applications. Because of improper lubrication in vacuum (Ueura, Kiyosawaa, Kurogi, Kanai, Miyaba, Maniwa, Suzuki, & Obara, 2008), metal-metal contact between the WG outer race and the inner side of the FS cup arises, leading to adhesive wear. This could affect the sliding movement between the WG and FS, which is also a function of the applied load, temperature, and input speed (Schäfer, Bourlier, Hantschack, Roberts, Lweis, Forster & John, 2005). The status of such a degradation could be detected by looking for inconsistencies among the angular positions and velocities of the input and output shaft of the gearbox.

External contaminants also negatively affect the bearing life. However, they have not been considered in the present study since industrial robots are usually built to satisfy specific IP standards (i.e., IP54 and IP64). Nevertheless, even if robots are improperly used in harsh environments and impurities enter inside the manipulator joint, sensors, like optical encoders, would be the first component to cease to work.

4.2. Tooth Wear

Since industrial manipulators are primarily used to execute repetitive tasks, each joint is subjected to a specific load history and different levels of wear. During a pick and place application, for example, it is more likely that the first three joints of the robot arm moves within predefined ranges, while the ones of the wrist are almost still since they usually have to maintain a constant orientation of the Tool Center Point (TCP). This could lead to improper lubrication of the FS and CS teeth, causing adhesive wear. As shown in Figure 5, the FS teeth are subjected to an uneven wear distribution along their length.

Figure 5. Effect of the coning angle on the flexspline tooth wear.

The damage is greater closer to the FS input than towards the rear cross section. This is caused by the coning angle generated by the insertion of the WG into the FS. This phenomenon is related to the fact that only the input section of the FS is deformed into an ellipse by the WG, while the output one, closer to FS boss, remains circular. This leads to an uneven engagement of the FS and CS teeth along the rotation axis, as schematized in Figure 6.

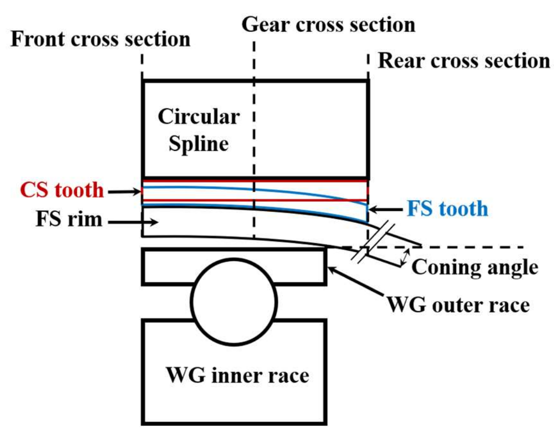

Figure 6. Uneven engagement between flexspline and circular spline caused by the coning angle.

The area closer to the FS front and gear cross sections is fully meshing with the CS, while in the remaining region there is almost no contact. Detailed studies about the FS stress as a function of the WG type are reported in Mahanto, Sahoo and Maiti (2018) and in Sahoo and Maiti (2016).

The presence of wear generates backlash, which is automatically compensated through the encoder used to close the position control loop in each joint. It could be detected by comparing command and feedback signals of the joint angular positions and looking for mismatches.

4.3. Lubrication

In harmonic drives there are three critical areas for lubrication:

- FS-CS tooth interface;
- WG bearing;
- WG-FS interface.

Accelerated Life Tests (ALTs) conducted by Li, Wang, Zhou, Pu and Wang (2015) proved that wear between the WG outer race and the inner side of the FS plays a key role in the HD efficiency, while the transmission accuracy is not affected. Roberts, Bridgeman, Jansson, Schulke and Tvaruzka (2015) suggest evaluating the trend of the axial load (F_a) acting on the WG and the gear output torque (T) to estimate the lubricating condition in this area. Such force is defined as:

$$F_a = 2 \cdot \frac{T}{D} \cdot \mu \cdot \tan(\theta) \quad (2)$$

where D is the gearbox size factor, provided by the manufacturer, θ is the pressure angle, usually equal to 20°, and μ is the friction coefficient at the WG-FS interface. However, this is feasible only if the gearbox is mounted on a specific test bench and properly sensorized. An alternative approach, which does not require dismounting the harmonic drive from the robot arm, is based on the dynamic parameters identification of the manipulator (Kovincic, Müller, Gattringer, Weyrer, Schlotzhauer & Brandstötter, 2019). This procedure allows estimating both Coulomb and viscous friction coefficients for each joint. However, since friction is affected by several factors, and not only by the status of the lubricant, this method has a limited efficacy.

The presence of an axial load acting on the WG is crucial in robotics applications, where motion laws are usually based on a trapezoidal trend of the joints angular velocities. The direction along which the axial force acts, in fact, changes according to the HD functionality as a speed reducer or as a brake. Continuous accelerations and decelerations cause a fluctuation of the axial force, leading to a periodic protrusion of the FS teeth from the CS (Ueura et al. 2008). Such sliding movements also affect the coning angle, which plays a key role in gearbox lubrication (Routh, Maiti & Ray, 2017). Moreover, joints torques are subjected to continuous fluctuations leading to repetitive changes in the magnitude of the axial force, which could lead to fretting fatigue.

4.4. Pitting

Repetitive stresses, which exceed the material resistance of the tooth surface, could lead to pitting. As for wear, this phenomenon is confined to the tooth region closer to the front and gear cross sections of the FS. The small particles detached from the tooth will mix with the lubricant, degrading it. Since the gearbox uses the same grease for all its components, the damage would spread not only to the FS itself, increasing wear, but also to the elliptical bearing and the contact interface between the WG and the FS. An example of such progressive loss of material is reported in Figure 7.

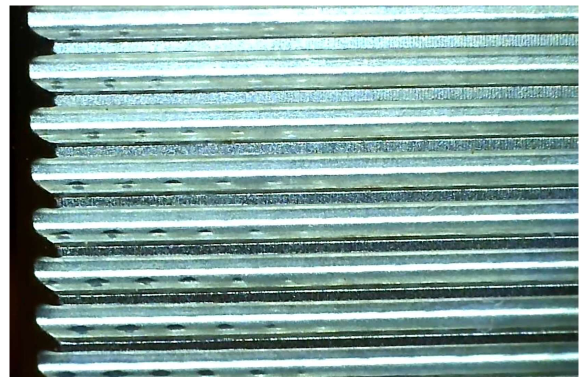

Figure 7. Pitting of the flexspline teeth detected on the shoulder joint of a UR5 collaborative robot.

Since pitting accelerates wear, it can be detected by analyzing vibration signals of the robot arm or looking for signs of backlash.

4.5. Ratcheting and Buckling

Another possible failure mode of harmonic drives occurs when excessive torque is applied. This could be related to external factors, like a heavy object falling on the robot, or incorrect transportation. In the case of a rotating gear, overload could make the CS and FS teeth not to properly engage. Such a phenomenon, called ratcheting, leads to eccentricity between the FS and the CS, followed by excessive vibrations and wear. In robotics applications, this could occur, for example, in case of an impact with the human operator. In this scenario, collision avoidance algorithms are fundamental not only for the operator's safety, but also to guarantee the correct operating condition of the industrial manipulator. On the other hand, if the input shaft is still when an excessive load is applied, the FS tends to buckle. The gear does not immediately cease to function, however, the loss of flexibility will lead to shear off the diaphragm from the FS cup (Schäfer, 2005).

4.6. Vibrations

According to Routh (2018), the main source of vibrations in HDs is caused by the continuous deformation of the FS.

Besides, mounting errors, geometric tolerances, and manufacturing defects also contribute to this phenomenon which can negatively affect the gearbox performance. Particular attention should be given to the resonance frequency f_n, defined as:

$$f_n = \frac{1}{2\pi} \cdot \sqrt{\frac{K_t}{J}} \quad [\mathrm{Hz}] \tag{3}$$

where K_t is the gear torsional stiffness, and J the load moment of inertia. The resonance speed ω_n of the gearbox output shaft can be derived as:

$$\omega_n = \frac{180 \cdot f_n}{\tau} \quad \left[{}^{\mathrm{deg}}/_{\mathrm{s}}\right] \tag{4}$$

Either this value should be passed quickly during acceleration and deceleration phases, or be avoided since it could contribute to the intensification of the FS wear and to crack propagation. Moreover, vibrations also affect the FS deformation leading to an improper engagement with the CS or to an irregular coupling with the WG.

A detailed investigation about the influence of flexspline length and thickness, unbalanced loads, and eccentricity on HDs vibration is provided by Masoumi and Alimohammadi (2013).

5. Cracks Propagation in Harmonic Drives

The most common failure mode of a harmonic drive is the FS fatigue fracture (Dong, Zhu, Zhou & Chen, 2012). As reported in Wang (2001), the presence of a crack can be early detected by analyzing the vibration signals of the gearbox. Since crack propagation and its effects differ according to its location, the four most probable regions of crack nucleation: rim, tooth, rear cross section, and diaphragm are analyzed. A schematic representation of the flexspline showing the aforementioned areas is reported in Figure 8.

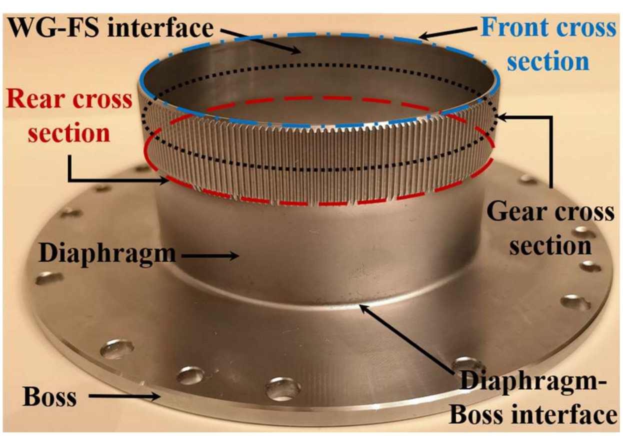

Figure 8. Flexspline of the harmonic drive used in the shoulder joint of a UR5 collaborative robot.

5.1. Rim Crack

According to Zheng and Yang (2018), the highest stresses acting on the FS are located at the tooth root surface. The crack can then follow two paths: through the tooth (TC) or into the rim (RC). Even though they are both undesired events, only the second one leads to a catastrophic failure. By approximating the flexspline to a spur gear, the studies conducted by Curà, Mura and Rosso (2014) and by Lewicki and Ballarini (1997) can be applied to the present case study. Experimental results showed how the backup ratio (*b*), defined as the ratio between the gear rim thickness (δ) and the tooth height (*h*), plays a key role in crack propagation. This information is critical for a failsafe design of the FS, whose thickness must be limited to allow a proper engagement with the CS. To minimize the risk of rim fracture, Lewicki (2002) suggests adopting gears with $b \geq 1.3$. An example of a failsafe design is provided by the HD used for the base, shoulder, and elbow joints of the UR5 collaborative robot from Universal Robots, where b=2.272. On the other hand, the FS studied by Routh and Maiti (2011) has a backup ratio of b=0.576, which leads to a higher probability of a catastrophic failure.

5.2. Tooth Crack

Since the flexspline is subjected to vibrations, especially under heavy loads and high speeds, cracks can also nucleate closer to the tooth tip, as shown in Figure 9.

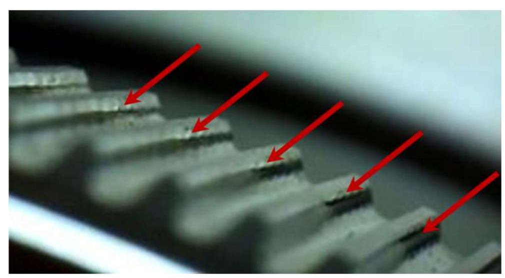

Figure 9. Flexspline tooth cracks.

This is also related to the fact that, even though the double-arc tooth profile provides the best performances in terms of position accuracy, it is characterized by higher stresses if compared with an involute one (Kayabasi & Erzincanli, 2007).

In contrast with the flexspline, a crack on the circular spline would always lead to a non-critical failure, since its backup ratio is much higher than the safety value of 1.3 suggested by Lewicki (2002). However, a tooth crack in the FS could propagate in a different way than one on the CS. In the case of thin-walled gears, in fact, Sahoo and Maiti (2016) highlighted how rim thickness can influence the percentage of load shared by the engaging teeth in spur gears. Since the force acting on the tooth has a paramount role in crack propagation and due to the fact that the FS and the CS have completely different values of backup ratios, this

Table 1. FMECA table of a harmonic drive gear

Failure mode	Effect	S	O	D	RPN
WG-FS interface wear	Lubricant contamination, efficiency loss, increment in the WG-FS sliding movement	3	10	6	180
Rear cross section crack	Vibration, total breakage of the gearbox	9	2	9	162
Lubricant degradation	Wear, increment of the wave generator axial load	2	10	8	160
Tooth wear	Backlash, vibration, uneven load distribution, lubricant contamination	3	10	4	120
Root tooth crack	Excessive vibration, efficiency degradation	7	4	4	112
Diaphragm crack	Vibration, decrement of the torsional stiffness, efficiency degradation	4	3	9	108
Tip tooth crack	Vibration, efficiency degradation	2	5	9	90
Pitting	Lubricant contamination and degradation, wear	1	10	9	90
Wave generator wear	Vibration, lubricant contamination, efficiency degradation	2	7	6	84
Rim crack	Excessive vibration, uneven load distribution, efficiency and accuracy degradation, total breakage of the flexspline	9	1	4	36
Buckling	Loss of FS flexibility, excessive vibration and wear	9	1	1	9
Ratcheting	Flexspline-circular spline eccentricity, vibration, and wear	7	1	1	7

information should be taken into account when studying such failure mode in harmonic drives.

According to Ma, Pang, Zeng, Wang and Wen (2015) and to Meng, Shi and Wang (2020), a tooth crack can be simulated by modifying the teeth meshing stiffness. A similar approach could be also adopted for rim cracks since they have a higher impact on the meshing stiffness than a TC.

5.3. Rear Cross Section Crack

Another possible fatigue failure of the FS could originate at the rear cross section (Dong, Zhu, Zhou & Chen, 2012). The stress in this area is also intensified by the coning angle.

Due to the deformation of the flexspline, the WG-FS interface does not correspond to the entire thickness of the elliptical bearing. Only an edge of the WG outer ring is fully in contact with the inside of the FS cup in proximity to its rear cross section. Nevertheless, since this region is not critical for the correct functioning of the HD, it would be probably more difficult to identify a crack at its early stage since its influence over the robot signals would be covered by noise. An example of a complete breakage of an HD, caused by fatigue failure initiated by a manufacturing defect in the rear cross section, is reported in Smith, Nick, Schuler, Kennett and Dillon (2019).

5.4. Diaphragm Crack

A crack at the diaphragm-boss interface also represents a common failure pattern in HDs (Li, 2016). This study suggests that it could be caused by both the deflection of the FS generated by the WG, and the external load. The output torque increases the shear stress on the FS diaphragm, leading to crack propagation. Since this region connects the oscillatory movement of the FS with the rotation of the gearbox output shaft, a crack in this area could reduce the FS torsional stiffness, leading to an increment of the joint position error.

6. FMECA Analysis of a Harmonic Drive

To detect the most probable failure modes related to harmonic drives and their effects on the robot behavior, an FMECA analysis is necessary. The results of this study are used to identify which faults and failures should be simulated using the High-Fidelity (HF) model of the harmonic drive introduced in section 7. Even though the proposed work is based on the use case of a UR5 cobot, it has general validity. Nevertheless, since the components used to build a robot are not standardized, FMECA of manipulators of different kinds and brands could lead to slightly different results from the ones reported in Table 1.

Because of the lack of data from the field, available only to the harmonic drive and the robot manufacturers, the proposed analysis should be considered as a first insight on the HD failure modes. Nevertheless, the values of Severity (S), Occurrence (O), and Detectability (D) reported in Table 1 are consistent with the information extrapolated from the literature and with the criteria reported in the 2020 SAE International report. Each index has been defined within a scale from 1 to 10:

- **Severity (S)**: a measure of the impact of the failure over the entire system. It ranges from the absence of an impact on the system (1) to a total breakdown of the machine with possible injuries to the operators without any prior warning (10);
- **Occurrence (O)**: the probability of occurrence of a failure mode for a specific time period. It goes from an extremely unlikely event (1) to an inevitable one (10);
- **Detectability (D)**: it defines whether symptoms or indicators of a certain failure mode can be detected through sensors or manual inspection. A higher score corresponds to a less probable detection probability. These values have been associated according to the possibility to identify the failure without dismounting the gearbox from the robot. The detectability of an

anomaly is then based on the analysis of vibration signals or data directly coming from the manipulator.

These three scores are then multiplied together to calculate the Risk Priority Number (RPN). The higher RPN, the more critical the failure would be. However, this technique has some drawbacks, and the final scores should be properly interpreted. As an example, for the proposed case study, the wear at the WG-FS interface results to be one of the most critical failure modes in harmonic drives. This is mainly related to the fact that such a phenomenon is inevitable in HDs and it cannot be easily identified by analyzing the robot signals. From here, the high values of occurrence and detectability, which lead to a large RPN. A similar scenario occurs with lubricant degradation. Since the robot joint is sealed, it would be necessary to dismount it to accurately verify the condition of the grease used inside the gearbox. As already mentioned, dynamic parameters identification algorithms could be adopted to estimate its health status, but friction coefficients can be influenced by other factors, like tooth or bearing wear.

To overcome these issues, the severity index plays a key role in risk assessment. In the case of similar RPNs, the priority would be given to the failure mode with a higher S rating. For this reason, a crack at the FS tooth root surface would have a much higher importance than the one at its tip, even if their RPNs are similar. Moreover, since HDs mounted on the UR5 have high backup ratios, such crack would never propagate through the rim. For this reason, even if it would cause a catastrophic failure, a rim fracture should not be considered as a priority for the case study under analysis.

Of particular interest, it is also the bottom of the FMECA table since, despite their high severity scores, buckling and ratcheting have very low RPNs. Such failure modes could be easily avoided by a correct implementation and usage of the manipulator and simply detected by the robot itself or due to the high vibrations of the robot arm.

7. Introduction to a Harmonic Drive High Fidelity Model

The lifespan of HDs is usually determined using accelerated life tests or their relative models, like the one proposed by Zhang, Wang, Wang and Wang (2015). However, they cannot be used to predict the gearbox remaining useful life. To do that, a kinematic and dynamic model of an HD is under development. It will be integrated inside a digital twin of a UR5 robot arm and used to evaluate the impacts of gearbox faults and failures on the entire manipulator. Simulated robot signals, acquired in both nominal and degraded conditions, will be collected to train DDMs for health features extraction. These data will be used to estimate the current status of the robot and its RUL.

The need for a new HF model of a harmonic drive comes from the lack of accurate models that could be used to effectively simulate faults and failures of different types and severity. In the past years, HDs models have been mainly devoted to better understand their performances and non-linear behavior. Particular attention has been given to estimate the kinematic error, defined as the difference between the expected and actual angular position of the output shaft of the gearbox. To do so Dhaouadi, Ghorbel and Gandhi (2003) and Preissner, Royston and Shu (2012) modelled the hysteresis phenomenon considering the harmonic drive as a black box. With the same purpose, a more accurate model of the HD is reported in Zou, Tao, Jiang, Mei and Wu (2017). Nevertheless, the level of detail adopted in the aforementioned studies is still not sufficient to describe any fault propagation mechanism. As an example, the forces exchanged at the FS-CS interface have been derived using an average value of the meshing stiffness. This approach, besides not taking into account the FS load asymmetry reported in Zou, Tao, Jiang and Mei (2013), does not allow analyzing the engagement of single tooth pairs, which is fundamental for PHM studies for HDs.

To overcome these limitations, a rigorous description of the interactions among the single elements of the harmonic drive should be adopted. Figure 10 shows the schematization of the level of detail adopted in the ongoing research campaign to simulate the presence of faults and failures in the gearbox.

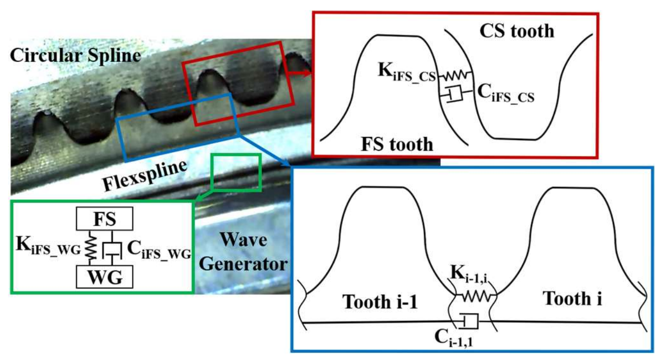

Figure 10. Schematic representation of the contact models used for the different interfaces in the harmonic drive.

The proposed model analyzes the interactions among the WG and the FS, the FS and CS and the FS tooth i with the previous and the next one. Within this framework, to simulate a rim crack at the tooth root, for example, the value of $K_{i-1,i}$ can be reduced, or even set to zero. On the other hand, to introduce a tooth crack, the meshing stiffness $K_{iFS\text{-}CS}$ would be modified. This approach is even more accurate for High Contact Ratio (HRC) gears, like harmonic drives. The percentage of stiffness reduction, in fact, is higher for gears with a higher number of teeth in contact (Pandya & Parey, 2013).

8. Conclusions and Future Developments

In the present paper, an overview of the failure modes in harmonic drive gears has been reported. Even though particular attention has been devoted to the field of both industrial and collaborative robotics, the proposed analysis has a general relevance. The fault-to-failure mechanism of each sub-component of the HD has been analyzed and possible methods for anomaly detection have been proposed. The outcomes of this analysis have been reported in an FMECA table from which an FTA analysis has been derived, providing an insight of the most common and critical failure modes in harmonic drive. These data will be used to simulate faults of different types and severity using a high-fidelity model of the gearbox, whose structure has been introduced.

Future works will be focused on the development and the validation of the proposed model and on the extraction of health features from simulated faulty robot behaviors for both diagnostics and prognostics purposes.

Nomenclature

ALT	Accelerated Life Test
b	Backup ratio
CBM	Condition Based Maintenance
CS	Circular Spline
D	Harmonic drive size factor
DDM	Data Drive Model
F_a	Axial force acting on the wave generator
f_n	Harmonic Drive resonance frequency
FMECA	Failure Mode Effects and Criticality Analysis
FS	Flexspline
FTA	Fault Tree Analysis
h	Tooth height
HD	Harmonic Drive
HF	High Fidelity
HI	Health Indicator
HM	Health Monitoring
J	Load moment of inertia
K_t	Harmonic drive torsional stiffness
MTBF	Mean Time Between Failures
PHM	Prognostics and Health Management
PPM	Planned Preventive Maintenance
RC	Rim Crack
RUL	Remaining Useful Life
T	Harmonic drive output torque
TC	Tooth Crack
TCP	Tool Center Point
TLE	Top Level Event
WG	Wave Generator
Z_{CS}	Number of the circular spline teeth
Z_{FS}	Number of the flexspline teeth
δ	Gear rim thickness
θ	Pressure angle
μ	Friction coefficient at the interface of the wave generator and the flexspline
τ	Gear ratio
ω_n	Resonance joint angular velocity

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