Corrosion Detection in Multi-Layered Rotorcraft Structures

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ABSTRACT

Rotorcraft structures do not readily lend themselves to quantifiable inspection methods due to airframe construction techniques. Periodic visual inspections are a common practice for detecting corrosion. Unfortunately, when the telltale signs of corrosion appear visually, extensive repair or refurbishment is required. There is a need to nondestructively evaluate airframe structures in order to recognize and quantify corrosion before visual indications are present. Nondestructive evaluations of rotorcraft airframes face inherent problems different from those of the fixed wing industry. Most rotorcraft lap joints are very narrow, contain raised fastener heads, may possess distortion, and consist of thinner gage materials (~0.012" - 0.125"). In addition, the structures involve stack-ups of two and three layers of thin gage skins that are separated by sealant of varying thickness. Industry lacks the necessary data, techniques, and experience to adequately perform routine corrosion inspection of rotorcraft.

In order to address these problems, a program is currently underway to validate the use of eddy current inspection on specific rotorcraft lap joints. Probability of detection (POD) specimens have been produced that simulate two lap joint configurations on a model TH-57/206 helicopter. The FAA's Airworthiness Assurance Center (AANC) at Sandia Labs and Bell Helicopter have applied single and dual frequency eddy current (EC) techniques to these test specimens. The test results showed enough promise to justify beta site testing of the eddy current methods evolved in this study. The technique allows users to distinguish between corrosion signals and those caused by varying gaps between the assembly of skins. Specific structural joints were defined as prime corrosion areas and a series of corrosion specimens were produced with 5-20% corrosion distributed among the layers of each joint. Complete helicopter test beds were used to validate the laboratory findings. This paper will present the laboratory and field results that quantify the EC technique's corrosion detection performance. Plans for beta site testing, adoption of the new inspection procedure into routine rotorcraft maintenance, and NDI training issues will also be discussed.

BACKGROUND

Historically, helicopter airframe fatigue evaluations have been based on the Safe Life approach. As part of the civil certification activity, damage tolerance assessments are also being carried out using the Residual Strength After Flaw Growth approach [1]. Initial results indicate that new inspections and shorter inspection intervals on existing inspections may be warranted. While helicopter service experience demonstrates that drastic changes in the inspection regime are not required, it may be necessary to supplement existing visual inspections with more sensitive NDI corrosion detection methods.

Also, because the practiced safe-life theories are reliability-based, the predicted crack initiation times are extremely conservative. Consequently, standard present-day maintenance procedures for helicopters can be costly and involve large amounts of spare parts [2]. The proper use of proven inspection techniques, accompanied by damage tolerance assessments, can be used to safely extend the life of helicopter components.
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Scheduled maintenance of many helicopter components targets corrosion detection. Typically, this requires extensive and costly tear-down and overhaul of frame members. Unfortunately, some of the overhauled structures do not always exhibit signs of corrosion. Without a nondestructive inspection (NDI) method of evaluating the faying surface of lap joints and structures before overhaul, unnecessary man hours and money may be spent. Furthermore, the application of noninvasive NDI for early corrosion detection could produce increased aircraft safety and reduced repair costs. Visual inspection for corrosion typically ranges from every two to twelve months depending on joint configuration and location. However, when corrosion indications are extensive enough to appear visually, repair or refurbishment is often required. Nondestructive evaluation of airframe structures is needed in order to recognize and quantify corrosion before visual indications are present. Rotorcraft that operate in corrosive environments such as coastal areas must be constantly maintained to reduce the likelihood of corrosion damage.

A corrosion inspection method, utilizing single and dual frequency eddy current techniques, and associated procedures have been developed and validated to address these concerns. The overall goal of this inspection is to resolve levels of corrosion above 10% total material loss in multi-layered lap joints and structures using multi-frequency eddy current techniques. Detection of total cumulative corrosion (thinning) over the entire riveted assembly is of primary interest while measuring corrosion levels in individual layers is a secondary goal. The approach presented here offers noninvasive inspections for helicopter airframes that focus on areas requiring maintenance and can ultimately reduce the down time of aircraft. Improved safety can also be achieved via more sensitive assessments that can be applied more often due to their ease of use.

Much of the larger, automated NDT equipment designed for inspection of aging fixed wing aircraft cannot be readily applied to rotorcraft structures simply because of the physical geometry of the joints involved. Also, the cost of such equipment can be a limiting factor. Thermography, ultrasound, and radiography were not evaluated for this application for a number of reasons, one of which is the false responses associated with air gap interfaces in porous sealant. The use of eddy current methods for corrosion inspections is common in the fixed wing aircraft industry [3]. Early investigations demonstrated the use of multiple frequency EC inspections to optimize detection and discriminate various flaw mechanisms [4]. Today's eddy current instruments are capable of operating at two or more test frequencies, displaying multiple channels of data, exciting more than one coil configuration, and combining or mixing raw data channels to generate new data channels. Prudent use of these instruments can help derive information about individual features of a complex, multi-faceted structure. Thus, eddy current (EC) is the chosen nondestructive corrosion detection method for the following reasons:

1. Dual frequency EC methods can resolve corrosion in multiple layers. If dual frequency EC inspections are combined with single frequency EC inspections, it is possible to delineate the level of corrosion in various layers.
2. Single and dual frequency EC equipment is readily available throughout the commercial industry and also at military maintenance depots.
3. Some of the areas targeted for inspection are difficult to access, and therefore, lend themselves to the use of small, hand-held probes.
4. The total thickness of aluminum to be inspected in any joint is approximately 0.200" or less, which is within the limits of the EC methods.
5. The equipment is small, portable, and relatively easy to operate.
6. Eddy current equipment can also be used for other tasks unrelated to this particular inspection (e.g. crack detection, coating thickness measurement).

Attempts at applying single frequency techniques for the detection of second layer corrosion have been unsuccessful. This is due to interfering signals caused by variations of the gap or separation between the first and second layer skins. The signals caused by this varying gap have been difficult to discriminate from corrosion when testing with a single frequency eddy current instrument.
Second and third layer corrosion detection requires the use of dual frequency techniques to eliminate unwanted response from varying sealant thickness between joint members. Though single frequency eddy current methods can be used to detect as little as 0.0016" of material loss through 0.048 inches of material (10% corrosion in a 3 ply stack of 0.016" thick aluminum) it cannot discern quantifiable amounts of corrosion at one layer vs. another. For example, if the actual joint is reduced by 5% at two adjoining areas between the second and third layers, the resultant A-scan signal will show 10% material loss. This situation can result in false rejection of the joint and possibly unnecessary aircraft downtime. Although a variable frequency technique exists for quantifying corrosion between multiple joint layers it has not been utilized to this point. Further evaluation was performed in this program to determine the accuracy and reliability of this technique.

**APPROACH FOR ASSESSMENT OF DUAL FREQUENCY EDDY CURRENT METHODS**

Nondestructive evaluations of rotorcraft airframes face inherent problems different from those of the fixed wing industry. Most rotorcraft lap joints are very narrow, contain raised fastener heads, may possess distortion, and consist of thinner gage material thickness (~0.012" – 0.125"). In addition, the structures involve stack-ups of two and three layers of the thin gage skins that are separated by sealant of varying thickness (See Figure 1).

The first task necessary for this project was to identify the specific structural lap joints on these aircraft that need to be inspected. From past experience and customer input it was determined that several joints are likely locations for corrosion initiation. These specific joints are historically susceptible to corrosion due to their location on the aircraft. For example, the lap joint between the nose of the aircraft and windshield is most likely to show the first signs of corrosion due to frequent moisture runoff. Another susceptible joint is comprised of thin titanium and aluminum fastened together. Over time the sealant between these two layers can become cracked or weathered allowing moisture to penetrate the joint. This moisture then aids the galvanic deterioration of the aluminum structure. There are five areas on the Bell
206 helicopter that can utilize the single and dual frequency eddy current technique. Figure 2 shows the key areas and Table 1 summarizes the structural configuration at each of these joints.

In an effort to evaluate EC for this study, probability of detection (POD) specimens were produced to simulate two lap joint configurations on the model TH-57/206 helicopter. Twelve test plates were designed measuring approximately 4" X 10" with each plate containing three rows of raised aluminum fasteners. The test specimens consisted of assemblies of two or three layers of aluminum to mimic the joints highlighted in Figure 2. The variables that were studied include: 1) proximity of corrosion to rivets (all rivets were buttonhead), 2) edge effects, 3) layer of corrosion contribution (1, 2, or 3), and 4) thickness of sealant separating the aluminum layers. The simulated corrosion areas varied in size, geometry, and severity, and were evenly distributed between joint layers, edges, and around rivets. A summary of the test specimen features follows.

Lap Joint Specimens with Engineered Flaws:
1. corrosion in aluminum plates was generated using a chemical etching process
2. riveted assemblies were produced with corrosion distributed in different layers: two layer stack-up of 0.32" plates; three layer stack-up of 0.16" plates
3. inspections were performed to assess probability of corrosion detection, ability to quantify corrosion levels, and ability to delineate flaw boundaries
4. corrosion levels - 5%, 10%, 15%, & 20% distributed evenly
5. corrosion areas - range from 0.2 in.\(^2\) to 3.1 in.\(^2\); majority of flaws in 1 in.\(^2\) range
6. corrosion sites within multi-layer stack-up are sometimes co-located.
The first specimen configuration, shown in Figure 3, is comprised of a stack of three 0.016-inch thick aluminum plates separated by varying amounts of Teflon tape and riveted together with buttonhead rivets (1" rivet spacing). This joint represents the area of the aircraft where the Plexiglas windshield joins the nose area of the rotorcraft (see Figures 1 and 2). This area is highly susceptible to corrosion primarily due to frequent moisture run-off. The second joint configuration, shown in Figure 4, is comprised of a stack of two 0.032-inch aluminum plates assembled similar to the first joint. This joint stack-up is representative of the cross member joint that runs between the two upper longerons aft of the titanium drip pan (see Figure 2). This joint is particularly hard to reach on some model aircraft and inspections may be further complicated by design modifications.

| Bell Helicopter Model 206/TH-57 Corrosion Inspection Candidate Areas |
|------------------------|------------------|
| **Structure**         | **Thickness of Layers** |
| Nose                  | 0.016", 0.016", 0.016" |
| Tailboom Fitting      | 0.125", 0.063", 0.032" |
| Tailboom Fitting      | 0.125", 0.080", 0.032" |
| Fwd to aft body splice; lower shell | 0.032", 0.020", 0.20" at rivet row |
| Fwd to aft body splice; lower shell | 0.032", 0.020" |
| Firewall longerons below engine compartment | 0.032", 0.032" |
| Nose shell            | 0.016", 0.16", 0.16" |

Table 1: Structural Make-Up of Areas for Application of Corrosion Detection NDI

Fabrication of the POD specimens was accomplished by coating each individual joint member with a chem-mill masking, and removing the masking from those areas designated to simulate material thinning. An entire corner from each plate was kept mask free as this was used as a dimensional witness pad. Actual material removal was accomplished by submersing each plate in 10 - 20 percent sodium hydroxide solution. The members were primed, stacked into final joint configuration with varying nonconductive shims inserted between each individual member (simulating the sealant), drilled, and riveted using raised head aluminum rivets. Figures 3 and 4 show sample test specimens with the corrosion in each layer labeled. The interaction of corrosion sites with varying shim (sealant) thickness regions is also shown.

A wide variety of lap joint configurations can be found in rotorcraft structure. Therefore, it was necessary to design eddy current standards representative of these lap joint areas. The standards have to be simple to use and universal by design. This means that each individual component (aluminum plate and shim simulating sealant) should be interchangeable so that a wide range of lap joint configurations can be simulated with only a handful of corroded plates. The resultant standards enable an inspector to literally reconstruct and simulate any joint on the aircraft in a matter of minutes and perform calibration for 10% corrosion of the thinnest joint member.
Figure 3: Three Skin Test Specimen for Probability of Corrosion Detection Study in Thin Gage Aluminum Structure

Figure 4: Two Skin Test Specimen for Probability of Corrosion Detection Study in Thin Gage Aluminum Structure

Shapes Indicate Corrosion Areas and Level of Corrosion
Shaded Areas Show Thickness of Various Nonconductive Shims
RESULTS FROM PROBABILITY OF CORROSION FLAW DETECTION STUDY

Figures 3 and 4 show the two types of blind test specimens (two layers of 0.032" thick skin and three layers of 0.016" thick skin). Twelve specimens were produced, six each of two layer and three layer skins. Single frequency EC tests (focusing on faying surface in outer skin) and dual frequency EC tests (focusing on all subsurface layers) were conducted by Bell and the AANC. The AANC used a Nortec 19e2 and Bell used Hocking Phaseac 2200 equipment. The multi-frequency EC technique was able to detect 5% material loss in individual and 2 or 3 layer stack-ups. The desired detection level for cumulative material loss over the thickness of the joint is 10%. The test specimens contained 47 flaw sites in 170 in.² of inspection area.

Typical A-scan output from the eddy current devices are shown in Figures 5-9. The figures show various responses corresponding to two and three layer assemblies, first, second, or third layer corrosion, and the effects of varying sealant thickness between adjacent skins on the eddy current response. The sealant was simulated using Teflon shims. The shape and location of the Teflon shims were randomized to create varying "gap" distances between adjacent plates. The shims ranged in thickness from 0.035" to 0.165" thick. They essentially create lift-off effects in the eddy current response which must be recognized and differentiated from corrosion signals.

While detection of total thinning through the entire structural assembly is the primary goal, it is helpful to provide additional insights into the distribution of the corrosion in the various skins. The use of the dual frequency method in conjunction with single frequency examinations allows inspectors to differentiate top layer corrosion from subsurface skin corrosion. However, it is not possible to separate second and third layer corrosion when they are co-located in their respective skins. Rather, the signal will indicate the sum of the corrosion in the two subsurface plates. Overall, the ability to detect 5% corrosion in 0.016" thick plate indicates that the technique is able to resolve thickness differences of less than 0.001".

Eddy current signals for first and second layer corrosion in a typical two skin stack-up are shown in Figures 5 and 6. Note that the sealant variation is only 0.007" so this signal is below the corrosion signals of interest (points 3-6 in Figs. 5 and 6). Figures 7 and 8 show signal responses acquired in three skin stack-up specimens. In these plots, the corrosion levels are clearly delineated. In Fig. 7, the equipment was set up to look for surface corrosion only (single frequency - inspection of faying surface in outer skin) so there was very little effect from the sealant thickness variations that existed beneath the top skin. In Fig. 8, the dual frequency capability of the equipment was used to detect and rank corrosion levels in the multiple layers. In this case, the corrosion was concentrated in the third layer. Also, there were no gap variations installed in the assembly so lift-off changes were not present to inhibit corrosion detection down to the third layer. An eddy current response array from a very complex structure is shown in Figure 9. This specimen contains corrosion in all three layers and a significant amount of sealant thickness variation. It can be seen that the responses at the different sealant levels are interspersed among the actual corrosion detection signals. However, it can also be seen that the corrosion areas provide unique and separate signals that can be distinguished. Operator experience and proper use of calibration standards will be key in properly identifying the signals. In addition, the required size and level of corrosion to be detected - conservatively held to 1 in.² area and 5%-10% material loss in this study - may allow the actual corrosion signals of interest to rise above the extraneous signals that might inhibit this inspection. At this time, a damage tolerance approach is being used to determine a clear accept/reject criteria for the inspections (i.e. size and severity of corrosion). This will allow us to make a final assessment of NDI performance in light of the actual inspection requirements.
(1) Probe Null (over air gap between plates)  (4) 5% Corrosion on Edge of 10% Corrosion Area

(2) Sealant Effects (0.007" th. Teflon between Plates)  (5) 10% Corrosion First Layer

(3) 5% Corrosion First Layer  (6) 15% Corrosion First Layer

Figure 5: Sample Eddy Current Signals from First Layer Corrosion in Two Layer Structure (2 X 0.032" th. plates)

(1) Probe Null (over air gap between plates)  (4) 5% Corrosion Second Layer

(2) Sealant Effects (0.007" th. Teflon between Plates)  (5) 10% Corrosion Second Layer

(3) 5% Corrosion First Layer  (6) 15% Corrosion Second Layer

Figure 6: Sample Eddy Current Signals from Second Layer Corrosion in Two Layer Structure (2 X 0.032" th. plates)
(1) Probe Null
(2) 10% Corrosion First Layer
(3) 15% Corrosion First Layer
(4) 20% Corrosion First Layer

Note: Equipment was set-up to detect surface (top layer) corrosion only so there were no effects from the Teflon/sealant variations in the assembly which ranged from 0.010" th. to 0.023" th.

Figure 7: Sample Eddy Current Signals from First Layer Corrosion in Three Layer Structure (3 X 0.016" th. plates)

(1) Probe Null
(2) 10% Corrosion Third Layer
(3) 15% Corrosion Third Layer
(4) 20% Corrosion Third Layer

Note: There were no gap variations installed in the plate assembly so lift-off changes were not present to inhibit corrosion detection down to the third layer.

Figure 8: Sample Eddy Current Signals from Third Layer Corrosion in Three Layer Structure (3 X 0.016" th. plates)
It should be noted that while the simultaneous use of single and dual frequency EC can uncouple corrosion between surface and subsurface structures, it is not possible to assign corrosion levels in each skin when the assembly has greater than two layers. The insights provided by the combined application of single and dual frequency EC are useful in assessing the joint but detecting total corrosion thinning across the assembly is the basic inspection goal. Overall, the NDI technique described here provides sufficient information to arrive at appropriate maintenance decisions regarding disassembly and repair.

The results above show that changes in "sealant" thickness (versus the sealant thickness at the chosen Null point) are the primary obstacles in deploying the eddy current inspection method. These changes in "sealant" thickness can induce signal variations much like those produced by actual corrosion. As a result, detailed NDI reference standards must be used and clear response calibration curves must be produced for the structure of interest. It should be noted that measurements on actual rotorcraft structure were not used to arrive at the 0.130" thick sealant variation used in this study. In fact, riveted assemblies should produce sealant variations of less than half this value. As a result, the eddy current curves show that the sealant effects should be below the corrosion detection curves for the desired threshold of 10% to 20%. Upcoming Beta site tests at maintenance depots will provide field data from operating rotorcraft. This data will provide further insights into the sensitivity of the dual frequency technique and also provide boundaries on the actual sealant variations that must be accommodated.

(1) Probe Null  (6) 20% Corrosion First Layer
(2) 0.007" Teflon "Sealant" Effects  (7) 5% Corrosion Second Layer
(3) 5% Corrosion First layer  (8) 0.0165" Teflon "Sealant" Effects
(4) 0.010" Teflon "Sealant" Effects  (9) 10% Corrosion Third Layer
(5) 15% Corrosion First Layer  (10) 20% Corrosion Second Layer

Figure 9: Sample Eddy Current Signals from First, Second, and Third Layer Corrosion in Three Layer Structure (3 X 0.016" th. plates)
Figures 10-12 are bar charts summarizing the inspection results for the two skin assembly, three skin assembly, and the overall results when all joint constructions are considered. The composite results from Bell and AANC showed that 81% of the flaws were detected. This is for flaws that were centered about 1" diameter in size even though it is anticipated that the desired detectable flaw size will be 2" dia. or greater. There were only three false calls among the 24 panel inspections and once a corrosion site was detected, the level of corrosion was correctly identified 86% of the time. The flaw shape was also correctly delineated 86% of the time.

![Rotorcraft Skin Corrosion Two Layer Structure](image)

**Figure 10: Corrosion Detection Results for Two Layer Rotorcraft Joint (0.032" th. X two)**
Figure 11: Corrosion Detection Results for Three Layer Rotorcraft Joint (0.016" th. X three)

Figure 12: Corrosion Detection Results for All Rotorcraft Joints
OUTCOME FROM FIELD TESTS ON AANC 206 ROTORCRAFT TEST BED

Field tests on a retired TH-57/206 helicopter were used to make conclusions regarding the viability of using NDT equipment to enhance current visual inspections for corrosion. Issues such as signal variations (masking effects caused by complexities of actual structure), anticipated sensitivities, and deployment impediments were investigated. The eddy current equipment deployed was Nortec 19e2 and Hocking Phaseac 2200. Formal inspection procedures were developed and reviewed during the testing and the supporting NDI Reference Standards were validated.

Overall, the inspections conducted on the 206 helicopter went well although there were some deployment difficulties in the nose area just below the windshield. In this area, there is a slight ridge in the rivet line that causes the probe response to be erratic. Other impediments include the small size of the joints being inspected and the ability of the probe to inspect only a subset of the entire joint surface area. The PoD inspection results, along with impediments identified in actual rotorcraft structures, are being reviewed in light of the required flaw size to be detected. Following is a summary of the approach that will be taken to implement the new multi-frequency eddy current inspection method for rotorcraft corrosion.

1. Although there are numerous rotorcraft that can utilize this inspection technique, the initial focus will be on the 206/TH-57 helicopter in order to quickly implement the NDT option. This will also help establish a track record since there is a current need in 206/TH-57 fleets especially within the Navy.
2. Bell will begin accumulating information on the structural configurations in other rotorcraft to prepare for a more universal application to the full spectrum of corrosion inspection needs.
3. NDT reference standards have been designed and fabricated using a modular approach. Users will not need to have a different reference standard for each stack-up variation but will be able to use a series of plates and Teflon sealant shims to produce the proper structural configuration. The plates will be bolted together rather than permanently riveted.
4. A clear accept/reject criteria will be established in order to make a final assessment of NDI performance.
5. The final phase of the validation effort will include field tests on operating helicopters. Participation is being solicited from both military and commercial maintenance depots. Results from the noninvasive EC inspections will be compared with the condition of the material found during subsequent disassembly of the structure.
6. The mode of adoption for the inspection process will be determined. The EC inspection will probably be listed as an alternate to existing visual inspections that require disassembly or as an alternate to component replacement.
7. Customer support interaction is also an issue. The training needs will be determined and other technology transfer activities will be addressed in order to assure proper implementation of the EC technique in the field.

CONCLUSIONS

Increased use of rotorcraft in both the commercial and military community has focused additional attention on inspection and maintenance practices. Furthermore, as the helicopter industry adopts the damage tolerance philosophy for designing and maintaining its aircraft, the appropriate application of nondestructive inspection (NDI) equipment will play a critical role in managing safety. There is a need to nondestructively evaluate helicopter structures in order to recognize and quantify corrosion before visual indications are present. Such applications of noninvasive NDI for early corrosion detection could safely extend the life of helicopter components and reduce repair costs.

Nondestructive evaluations of rotorcraft airframes face inherent problems different from those of the fixed wing industry. Most rotorcraft lap joints are very narrow, contain raised fastener heads, may
possess distortion, and consist of very thin gage materials. In addition, the structures involve stack-ups of two and three layers of the thin gage skins that are separated by sealant of varying thickness. This study established the viability of eddy current methods to supplement visual inspections with more sensitive corrosion detection.

A corrosion inspection method, utilizing single and dual frequency eddy current techniques, has been developed and validated. Controlled probability of flaw detection activities proved that this NDI method is able to resolve levels of corrosion below 10% total material loss in multi-layered lap joints and structures. Detection of total cumulative corrosion (thinning) over the entire riveted assembly was shown and some ability to delineate corrosion levels in individual layers was also demonstrated. The method is able to uncouple signals of interest from unwanted signals that can produce misleading inspection results (e.g. lift-off effects from sealant between skins). Preliminary evaluations on helicopter test beds were encouraging and formal adoption of the technique, via inclusion in Nondestructive Testing Manuals, will occur after successful field testing at several commercial and military maintenance depots.

One of the concerns of owners and operators of rotorcraft is the cost associated with maintenance. It is the intent of this study to help the owners and operators to enhance safety and lower maintenance costs through the application of more sensitive inspection practices. The multi-frequency eddy current technique was developed using currently available eddy current devices to show that this inspection can be readily integrated into rotorcraft maintenance programs. However, the maintenance facility must have the proper personnel and equipment to handle the challenge of this nondestructive testing. The personnel must have basic NDI qualifications and the facility must be able to provide adequate training in order to adopt new and advanced NDI techniques. This infrastructure may be lacking at the smaller maintenance facilities. One aspect of this joint FAA-industry effort is to facilitate technology transfer so that new inspection practices can be safely adopted throughout the rotorcraft industry. Technology transfer activities include the development of written NDI procedures, design of NDI references standards, and training assistance so that all maintenance facilities can utilize these advanced NDI techniques in a cost effective manner. With sufficient technical training, proper standards, and knowledge of specific joint configurations, multi-frequency eddy current inspections for corrosion can provide improved maintenance practices and decreased cost in all rotorcraft maintenance depots.

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