Life Prediction Method of On-board Hydrogen Clock under Multiple Mechanisms

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Abstract. As the on-board time reference of the navigation system ranging, the on-board hydrogen clock is the core part of the payload of the satellite navigation system, and its lifetime directly determines the duration of the navigation satellite mission. In order to meet the demand for life prediction of on-board hydrogen clocks, this paper expounds the composing and design of the hydrogen clock and focuses on the factors affecting the lifetime. In general, the factors include: the hydrogen supply period of the hydrogen component in the vacuum module, the period of the vacuum system to maintain a specific vacuum degree, the degradation speed of the bulb coating, the atomic preparation ability including the ionization device of the ionization bulb and the ionization circuit, the performance of the magnetic shielding and other key factors. In addition, the key performance indicators are also considered. The telemetry data and the test data of the key components on the ground are comprehensively utilized to evaluate the lifetime at which the relevant performance parameters reach the threshold. Based on the random failure, degradation, consumption and the key performance indicators of the hydrogen clock, a multi-mechanical and competitive life prediction method is proposed. The case study shows that the new method can be used to get the more dependable results of life prediction.

1. Introduction

The global satellite navigation system is an important infrastructure of a country. It transmits high-precision, all-weather positioning navigation and timing information, which is a valuable information resource that can be shared by military and civilian users. In satellite navigation and positioning, the key to accurate position measurement is the measurement of precise time. The high-precision time is established and maintained by a high-precision atomic clock. As the on-board time reference of the navigation system ranging, the on-board hydrogen clock is the core part of the payload of the satellite navigation system, and its lifetime directly determines the duration of the navigation satellite mission. Therefore, it is of great significance to predict the life of the on-board hydrogen clock.

Due to the characteristics of high functional density and long service time, atomic clocks are usually required to be equipped low weight, low power dissipation, high reliability and excellent stability. There are many types of on-board atomic clocks, such as on-board rubidium atomic clock, on-board cesium atomic clock, and on-board hydrogen atomic clock. These types of atomic clocks are traditionally widely used on the ground for engineering applications. At present, the research on life prediction of on-board atomic clocks is mainly focused on on-board rubidium atomic clock and on-board cesium atomic clock [¹][²]. The research on on-board hydrogen atomic clocks is focused on
system design and performance improvement. Due to the complexity of the on-board hydrogen clock, there are very few studies on the life prediction of the whole equipment. The main developer of foreign space-borne hydrogen clocks is the Swiss company Spectra Time, which provides hydrogen clocks for Galileo systems in Europe. The company has carried out some reliability and life tests, including: long-term variance diode drift assessment, continuous monitoring of hydrogen clock atomic transition signals, long-term assessment tests of microwave resonant cavity frequency drift, and hydrogen source outgassing test. The company has built a hydrogen clock life assessment platform in the ground laboratory, which is composed of a vacuum maintenance system, a temperature control system, a status monitoring system and a performance test system to simulate the on-orbit working conditions of a on-borne hydrogen clock. The hydrogen clock is placed in the platform for long-term continuous work assessment, which provides a basis for reliability and life evaluation.

Therefore, various factors such as sudden failure, degradation and consumption should be fully considered in the accurate life prediction, and the key factors affecting the life of the satellite hydrogen clock should be analyzed. Aiming at the requirement of life prediction of on-board hydrogen clock, this paper comprehensively considers random failure, degradation, consumption, and the key performance parameters of hydrogen clock in orbit, and proposes a multi-mechanical and competitive life prediction method, so as to obtain a more reasonable life prediction result.

2. Overall design of on-board hydrogen clock

2.1. Working principle of atomic clock
According to the principle of quantum mechanics, atoms have discontinuous energy values. When the atomic transition is from one energy level to another, the frequency of electromagnetic waves absorbed or released is fixed. The atomic clock is an instrument that uses a fixed frequency electromagnetic wave generated by atomic transitions.

2.2. Satellite navigation and satellite time
The wide application of hydrogen clock in navigation satellite has promoted the rapid development of atomic clock technology. At present, the global satellite navigation system mainly includes the GPS navigation system of the United States, the GLONASS navigation system of Russia, the Galileo navigation system of Europe and the Beidou navigation system of China. The basic principle of the four major satellite navigation systems is that the user terminal calculates local coordinates by measuring the distance from the signals of four or more satellites in space to the user terminal to perform positioning. A radio signal transmitted by a satellite in the space carries the satellite time and location. After reaching the ground over a distance of 20,000 to 30,000 kilometers, it is received by the ground terminal, and the satellite signal time is extracted and compared with local time to obtain the propagation time of the signal. The distance between the satellite and the ground can be obtained by multiplying the propagation time by the speed of light. Because the speed of light is very fast, accurate positioning requires high accuracy in measuring time. For example, when the time measurement error is 10ns, the corresponding spatial distance error reaches 3m. The requirements for positioning in daily activities are basically several meters, which requires that the satellites in space have good time retention ability, and the time difference between each satellite needs to be kept within a few nanoseconds.

2.3. On-board hydrogen clock mechanism
A hydrogen atom consists of a nucleus and a valence electron. The total angular momentum of the ground-state electron is 1/2 and the nuclear spin is 1/2. Therefore, the ground state of the hydrogen atom has two hyperfine energy levels F₁ = 0 and F₂ = 1. In the external magnetic field, the F₂ = 1 energy level is divided into three hyperfine magnetic energy levels, while the F₁=0 energy level is still one. The transition used in the hydrogen atom oscillator is a transition (F = 1, mF = 0) <=> (F = 0, mF = 0), and the corresponding frequency is 1420.405751 MHz, which is not convenient as a
frequency reference because of the high frequency. Usually, phase-locked or frequency-locked circuits are used to lock the 5 MHz or 10 MHz frequency of the crystal oscillator output to this frequency, so as to obtain high-precision frequency signals [3].

According to its working mechanism, hydrogen clock can be divided into two types: active type and passive type. The active hydrogen clock has a large volume and can realize the autonomous atomic transition. The passive hydrogen clock is relatively small in size and only occurs the atomic transition under the excitation of a detection signal. In order to meet the needs of satellite carrying, the on-board hydrogen clock adopts passive hydrogen clock technology, which locks the 10 MHz crystal frequency to the atomic transition frequency through a frequency-locked loop.

2.4. The composition of on-board hydrogen clock
The on-board hydrogen clock consists of a physical part and an electrical part. The physical part is composed of a cavity bubble system, a vacuum system, a atom placement system, a magnetic shielding system, a collimation and state selection system. The cavity bubble system includes a microwave resonance cavity, an atomic storage bubble, a varactor and a supporting structure, etc. The vacuum system includes a vacuum adsorption pump, an ion pump, and a supporting and sealing structure. The atomic preparation system includes a hydrogen cylinder, a main nickel tube purifier, an ionization source, a collimator and a magnetic separator. The magnetic shielding system consists of layers of magnetic shielding and its supporting structure [3].

The circuit mainly consists of the main electronic circuit and the auxiliary electronic circuit. The main circuit includes a thermostatic voltage-controlled crystal oscillator, a detection circuit, an isolation amplifier circuit, an up-conversion circuit, a digital servo and a frequency synthesizer circuit. The auxiliary circuit includes a thermostatic circuit, a high-voltage power supply and a constant current source [3].

The physical part of the on-board hydrogen clock stores about 40 liters of hydrogen. After purification by a nickel purifier, the hydrogen is ionized into an atomic state in an ionization bubble. Through the collimation and state selection system, high-level hydrogen atoms in the ground state are injected into the storage bubble in the microwave resonance cavity, and a microwave signal of an appropriate frequency is injected into the microwave vibration cavity to generate microwave resonance in the cavity. In this way, the atoms can generate stimulated radiation in the storage bubble, which increases the microwave energy in the cavity. By detecting the microwave energy in the microwave resonator, the microwave signal output by the circuit system can be locked on the atomic transition spectrum, and the output signal with high stability and accuracy can be obtained. This process needs to maintain high vacuum through the vacuum system, and the magnetic shielding system shields external magnetic field interference.

The circuit mainly consists of two locked loops: the atomic transition locked loop and microwave cavity servo control loop. Its main function is to lock the crystal frequency to the atomic transition frequency and the microwave cavity frequency to crystal frequency. In order to ensure the long-term stable operation of the passive hydrogen clock, an auxiliary electronics system is required to ensure that the physical part remains stable. In the auxiliary electronics system, the constant current source acts on the nickel reservoir to ensure stable hydrogen entry into the system. The thermostatic circuit is used to maintain the temperature stability of the physical part, so as to ensure that the hydrogen atoms in the storage bubble maintain a constant flight rate. The high-voltage power acts on the titanium ion pump to realize the absorption of vacuum inert gas and carbon dioxide.

3. Overall design of on-board hydrogen clock
The on-board hydrogen clock is required to have an in-orbit working life of 12 years. Due to the multi-disciplinary, multi-objective, multi-coupling and multi-constraint characteristics of the hydrogen clock, it is necessary to analyse the factors affecting the life of the hydrogen clock. In general, the factors affecting life include: the hydrogen supply period of the hydrogen component in the vacuum module, the period of the vacuum system to maintain a specific vacuum degree, the
degradation speed of the storage bulb coating, the atomic preparation ability including the ionization device of the ionization bulb and the ionization circuit, the performance of the magnetic shielding and other key factors. In addition, parameters such as ionization bulb intensity and second harmonic amplitude are also key factors affecting the index of the hydrogen clock, so they are also included in the scope of life research. In this paper, the above influencing factors are sorted out and the life model is divided into three categories: degradation model, life consumption model and random model. In addition, the key indexes that affect the performance of hydrogen clock are comprehensively utilized to establish the life influencing factor tree, as shown in figure 1.

3.1. Life consumption model
Assuming there are m independent consumption factors, the consumption life of hydrogen clock depends on the fastest one, as follows:

\[ T_c = \min(T_{11}, T_{12}, \ldots, T_{1m}) \]  

(1)

Where, \( T_{ij} (i = 1, 2, \ldots, m) \) is the estimated life of the i-th factor, which can be calculated according to the life model of each consumption factor.

According to the law of hydrogen consumption, the amount of hydrogen supplied by the hydrogen source is more than twice that required for the working life of the hydrogen clock, leaving a sufficient margin. Therefore, the life consumption model focuses on the vacuum maintenance system.

The titanium pump is responsible for removing the inert gas in the vacuum and maintaining the high vacuum state of the vacuum system. The titanium pump generates a Penning discharge within high voltage and high magnetic field, thus adsorbing gas molecules in the container to achieve vacuum. However, the titanium ion pump will cause the loss of the titanium plate during the process of ion bombardment and suction. The titanium pump would fail when reaching a certain amount of inhalation, and the failure rate is proportional to the total amount of ion bombardment. Generally, if the working current of the titanium pump is less than 5μA under normal working condition, the current has a linear relationship with the vacuum, as shown in The life characteristic of the titanium pump is the working current. The life of titanium pump is determined by the product of working load (i.e., working current) and working time. Under the failure state, the current of titanium pump will produce irregular pulsation, and in severe cases, the current will greatly exceed the normal value.
Figure 2. The relationship between the pump current and pressure.

In the vacuum system of hydrogen clock, there are differences in the suction efficiency of the adsorption pump and titanium pump for different gases, so they cooperate with each other and work at the same time. When we take influences such as the solubility and temperature of the adsorption pump into consideration, it has been verified through experiments that the life of the pump could still reach 2.5 times the normal working life in the most extreme cases. Therefore, the life consumption model of titanium pump is mainly investigated.

A life evaluation model of the titanium pump was established with the operating current as the characteristic parameter. This characteristic parameter obeys the normal distribution with mean value \( \mu(t) \) and standard deviation \( \sigma(t) \). \( \mu(t) \) is monotonically with the increase of time. When the threshold of the characteristic parameter is reached, the product reaches its lifetime. Under the condition of a given confidence level \( \gamma \), the relationship between the confidence lower limit and the confidence level of the product life \( \gamma \) is shown as follows.

\[
P(Y(t) \geq V_T) = \gamma
\]

(2)

Where, \( Y(t) \) is the variation law of the current of titanium pump and \( V_T \) is the threshold value.

Determine \( k \) test moments \( t_i \) \((i = 1, 2, \cdots, k)\), take \( n_i \) samples at \( t_i \) and measure their value \( y_{ij} \) \((i = 1, 2, \cdots, k; j = 1, 2, \cdots, n_i)\), then:

\[
Y(t) = \mu + \delta = \alpha + \beta t + \delta
\]

(3)

On the premise that the test data are independent of each other, the least square method can be used to estimate the values \( \hat{\alpha} \) and \( \hat{\beta} \) of \( \alpha \) and \( \beta \).

\[
\hat{\beta} = \frac{\sum t y - n \bar{t} \bar{y}}{\sum t^2 - n \bar{t}^2}
\]

(4)

\[
\hat{\alpha} = \bar{y} - \bar{t}
\]

Where:

\[
\bar{t} = \frac{1}{n} \sum_{i=1}^{k} n_i t_i \quad , \quad \sum t^2 = \sum_{i=1}^{k} n_i t_i^2 \quad , \quad n = \sum_{i=1}^{k} n_i \quad , \quad \bar{y} = \frac{1}{n} \sum_{i=1}^{k} \sum_{j=1}^{n_i} y_{ij} \quad , \quad \sum t y = \sum_{i=1}^{k} t_i \sum_{j=1}^{n_i} y_{ij} \quad , \quad \sum y^2 = \sum_{i=1}^{k} \sum_{j=1}^{n_i} y_{ij}^2
\]
For a given confidence level $\gamma$, the lower confidence limit for product life satisfies the following equation.

$$Y(t) = \hat{\alpha} + \hat{\beta}t^* + t_{1-\gamma} (n-2)^{\frac{n+1}{n}} + \frac{(t^*-t)^2}{\sum t^2 - nT^2} \delta$$  \hspace{1cm} (5)

The currents of four titanium pumps are shown in figure 3. $\hat{\alpha}$ and $\hat{\beta}$ are 48275 and -2.9 respectively.

![Figure 3. The current of titanium pump.](image)

3.2. Degradation model

Assuming there are $n$ independent degradation failure factors, the degradation life of hydrogen clock depends on the fastest one, as follows:

$$T_d = \min(T_{21}, T_{22}, \ldots, T_{2n})$$  \hspace{1cm} (6)

Where, $T_{2j}$ ($j = 1, 2, \ldots, n$) is the estimated life of the $j$-th factor, which can be calculated according to the life model of each degradation factor.

3.2.1. Degradation model of magnetic shielding system

When the hydrogen clock works, the resonance transition of the hydrogen atom needs to be carried out in a low magnetic field environment. Therefore, a magnetic shielding system is necessary to isolate the atomic system from the external magnetic environment. Different from the ground operating environment, the magnetic shielding system is affected by long-term alternating magnetic field when it is in orbit. This environment will repeatedly charge and discharge the magnetic shielding system, which will cause the magnetic shielding coefficient to decrease slowly and affect its working life.

A magnetic shielding aging and performance test platform was established to simulate the magnetic field environment in orbit. According to the test data, the performance change curve of the magnetic shielding system was drawn with the test time as the abscissa value and the shielding coefficient as the ordinate value, as shown in figure 4.

It can be seen from the test results that the external periodic magnetic field will affect the shielding performance of the magnetic shielding system. When the magnetic shielding system adapts to the external environment, the shielding coefficient returns to a higher level and has a slowly decline. Therefore, the stable performance curve of the magnetic shielding system is fitted to obtain the degradation model of the magnetic shielding system, as shown in figure 4.
\[ y = -3.4496T + 47509 \] (7)

Where, \( y \) is the shielding coefficient, and the threshold is 30000. \( T \) is the operation time.

3.2.2. Degradation model of ionized bubbles

BBC News reported that across the 18 satellites of the European Galileo Navigation System now in orbit, nine clocks out of 72 have stopped operating. Analysts believe that the fault is the ionization bubble. It is probably caused by defects accumulated on the surface of the ionized bubble during the working process, resulting in the defect layer, which makes it difficult for the RF signal power to excite hydrogen molecules in the ionized bubble, affecting the start of hydrogen clock. The reduction of SiO\(_2\) is the main reason for the contamination of quartz glass under the atmosphere of hydrogen plasma. The relationship between the change rate of the transmittance of quartz glass and the amount of H\(^+\) radiation injected can be obtained through experiments. Through the relevant experiments, it can be known that the formation and evolution of defects caused by irradiation is positively related to the degradation of optical properties of quartz glass. The evolutionary dynamic equation of the transmittance change rate of quartz glass under H\(^+\) irradiation can be described as:

\[
\Delta T = T_1 \left[ 1 - \frac{1}{(1 + k_1 \varphi)k_2} \right] + T_2 \left[ 1 - \exp(-k_3 \varphi) \right] 
\] (8)

Where, \( T_1 + T_2 \leq A_0 \) (\( A_0 \) is the initial absorbance of quartz glass). \( T_1 \) is the parameter representing the weight of radiation-induced defect formation rate on absorbance. \( T_2 \) is the parameter representing the influence of radiation-induced defect relaxation coefficient on absorbance. \( \varphi \) is the irradiation flux of charged particles. \( k_1 \) is the model parameter related to irradiation parameter, defect complex coefficient of damage section, etc. \( k_2 \) is a model parameter related to the efficiency of the ionization effect and the property of the material itself. \( k_3 \) is the relevant parameter to characterize the defect relaxation in the coating.

3.3. Random failure model

Random failure products may fail at any time. The circuit part is a random failure type and obeys the exponential distribution. The reliable life of the circuit is:
\[
T_r = -\frac{1}{\ln R(T_r)} = -\frac{1}{\lambda_0} \ln(1 - \eta) 
\]  
(9)

Where, \( \lambda_0 \) is the failure rate of the circuit, and the estimation of \( \lambda_0 \) is \( 5 \times 10^{-5} \). \( R(T_r) \) is the reliability at the time \( T_r \) of the circuit part, \( \eta \) is a random number and \( 0 < \eta < 1 \).

### 3.4. Key performance indicators

Assuming there are \( p \) independent factors of key performance indicators, the life of hydrogen clock determined by key indicators depends on the fastest one, as follows:

\[
T_K = \min\{T_{31}, T_{32}, \ldots, T_{3p}\} 
\]  
(10)

Where, \( T_{3k} (k = 1, 2, \ldots, p) \) is the estimated life of the \( k \)-th factor, which can be calculated according to the life model of each key indicator.

Based on the development experience and in orbit operation, the key parameters of the reliability and life of the hydrogen clock were determined as the voltage of voltage-controlled crystal, varactor diode voltage, high-voltage source current, second harmonic amplitude, ionization light intensity, frequency performance, etc. Among them, the high-voltage source current reflects the maintenance of the vacuum, and the second harmonic amplitude reflects the atomic transition of the physical part. Since the hydrogen clock has been in orbit for a period of time, the two are in a stable state and there is no decline. The ionization light intensity reflects the working condition of the ionization source circuit, but only reflects the light transmittance of the ionization bubble and does not affect the performance. Frequency is the most important performance indicator of a hydrogen clock and it is only an important criterion for reliability. Therefore, the effect of the voltage of voltage-controlled crystal and varactor diode voltage are mainly considered.

### 3.4.1. The telemetry of the voltage of voltage-controlled crystal

The telemetry of the voltage of voltage-controlled crystal can reflect the crystal lock and long-term aging. The variation trend of this indicator can be obtained by analysing the in-orbit test data, as shown in figure 5. Fitting this curve gives:

\[
Y = -0.0091X + 1.4868 
\]  
(11)

Where, \( Y \) is the voltage of voltage-controlled crystal, which should be greater than zero. \( X \) is the operation time.
3.4.2. The telemetry of varactor diode voltage
The telemetry of varactor diode voltage reflects the locking and aging of microwave cavity. The variation trend of this indicator can be obtained by analysing the in-orbit test data, as shown in Fig.5. Fitting this curve gives:

\[ Y = 0.033X + 1.0905 \]  

(12)

Where, \( Y \) is the varactor diode voltage, and its threshold is 4.5. \( X \) is the running time.

4. Simulation model of life prediction of hydrogen clock

4.1. The life model of hydrogen clock under multiple mechanisms
According to the analysis in Chapter 3, the lifetime of the on-board hydrogen clock under multiple mechanisms is:

\[
T_{\text{life}} = \min(T_c, T_d, T_r, T_K) \\
= \min\left[ \min(T_{11}, T_{12}, \ldots, T_{1m}), \min(T_{21}, T_{22}, \ldots, T_{2n}), T_r, \min(T_{31}, T_{32}, \ldots, T_{3p}) \right] 
\]

(13)

4.2. Simulation analysis process
Based on the life consumption model, degradation model, random failure model and life model determined by key performance indicators, the Monte Carlo simulation method can be used for life prediction. The simulation process is shown in figure 6. The specific process is described as follows.

(1) Set the initial conditions
The initial conditions include the parameter values of each life model, the working time of the hydrogen clock, the simulation times, etc.

(2) Estimate the remaining life determined by random failure
According to the random failure model obeyed by the hydrogen clock, the Monte Carlo simulation sampling formula is used to generate the random failure time \( T_1 \). If \( T_1 \) is greater than the working time \( T_0 \), the remaining life \( T_r = T_1 - T_0 \) is determined by the random failure in this simulation. If \( T_1 \leq T_0 \), then this simulation is invalid and directly enters the next simulation to generate the value of \( T_1 \) again.

(3) Estimate the remaining life determined by the consumable substances
According to the consumption law of the consumable substances, the remaining life \( T_{2i} (i = 1, 2, \ldots, m) \) of each consumption factor can be obtained, and the minimum value is selected to obtain the remaining life \( T_c \) in this simulation.

(4) Estimate the remaining life determined by the degradation failure
According to the degradation law of various degradation factors, the remaining life \( T_{2j} (j = 1, 2, \ldots, n) \) of each degradation factor can be obtained, and the minimum value is selected to obtain the remaining life \( T_d \) in this simulation.

(5) Estimate the remaining life determined by the key performance indicators exceeding thresholds
According to the change trend of various key indicators, the remaining life \( T_{3k} (k = 1, 2, \ldots, q) \) of each indicator can be obtained, and the minimum value is selected to obtain the remaining life \( T_K \) in this simulation.

(6) Determine the remaining life of the hydrogen clock \( T_{\text{life}} \) in this simulation
According to Eq. (13) of the hydrogen clock life based on the competition model, \( T_r, T_c, T_d \) and \( T_K \) are compared and the minimum value is selected, that is, the remaining life of the hydrogen clock in one simulation is obtained.
(7) Calculate the average remaining life of the hydrogen clock $\bar{T}_{\text{life}}$

Repeat the step (2) to (6) for $N_e$ cycles, where $N_e$ is $1 \times 10^6$ in this paper. Thus, $N_e$ remaining life values are obtained, and the average remaining life of the hydrogen clock is:

$$\bar{T}_{\text{life}} = \frac{\sum_{i=1}^{N_e} T_{\text{life}}}{N_e}$$  \hspace{1cm} (14)

The simulation shows that the average life of the hydrogen clock is 13.3 years.
5. Conclusion

The end-of-life of the hydrogen clock is the result of three mechanisms: random failure (abrupt failure), degradation failure and consumption failure. By analyzing the life characteristics of hydrogen clock, the life prediction analysis under multiple mechanisms shows that:

1) Using only random or consumable failure to estimate the residual life of a hydrogen clock may yield overly optimistic results. Accurate life predictions should cover three types of factors: random failure, degradation and consumption.

2) This method comprehensively utilizes the ground development and in-orbit data and considers a variety of factors affecting the life, which theoretically has higher credibility and is more suitable for engineering applications.

As the hydrogen clock serves as the on-board time reference and plays an important role in providing continuous services for satellite navigation system, it is of great significance to accurately predict the life of hydrogen clock. At the same time, due to the multi-disciplinary, multi-coupling, multi-constraining characteristics of the hydrogen clock, a lot of research work is still needed to be carried out on life prediction of the key components and decoupling of the key parameters.

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