3-4 Hydrogen Maser

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Communications Research Laboratory (CRL) plays an important role in development of hydrogen maser in Japan. In this paper we describe the history of development of the hydrogen maser in CRL, and the principle of the hydrogen maser. Further, as a recent topic, we also describe the development of the space-borne hydrogen maser.

Keywords

Atomic frequency standard, Hydrogen maser, Space-borne hydrogen maser, Frequency stability, Sapphire loaded cavity

1 Introduction

1.1 Background of research and development at the CRL

The development of the hydrogen maser at the Communications Research Laboratory (CRL) began in 1965. In the following year (1966), the CRL succeeded in producing the third hydrogen maser oscillator in the world, after the United States and Switzerland. The CRL subsequently made its research results available to Anritsu Corporation, permitting the latter to place commercial hydrogen masers on the market, which are now in use at various research facilities in Japan.

In addition, recently the CRL has been developing a space-borne hydrogen maser for a global positioning system in collaboration with Anritsu Corporation, publicizing its research results at a variety of national and international academic gatherings.

1.2 Features of hydrogen maser and comparison to other atomic frequency standards

In addition to the hydrogen-maser frequency standard, major atomic frequency standards in practical use include the following:

- Rubidium atomic frequency standard
- Cesium atomic frequency standard

Fig.1 shows the general frequency stabilites of atomic frequency standards.

The rubidium atomic frequency standard uses a gas cell in which rubidium atoms are confined; it can be miniaturized and made lightweight, and is widely applicable as a reference signal source in the communications and broadcasting fields. The rubidium atomic frequency standard is inferior in terms of long-term stability relative to the cesium atomic frequency standard, although its frequency stability in the short term is comparable with that of the latter.

The cesium atomic frequency standard creates a reference frequency by exciting heated cesium atoms in a vacuum and causing the excited atoms to interact with a microwave. This standard is characterized by its superior long-term stability, and has led to a scientific definition of the second based on the transition frequency of a cesium atom. As a result, standards research organizations in Germany, France, Italy, the U.S., and Japan operate cesium atomic primary frequency standards, providing reports on accuracy to the Bureau International des Poids et Mesures (BIPM), contributing to the overall accuracy of TAI. The CRL also operates an optical-pumping cesium atomic primary frequency standard (CRL-O1), and reports on its accuracy to the BIPM several times a year.

On the other hand, atomic-fountain-type

cesium primary frequency standards have recently begun to be promoted as being capable of greater frequency accuracy. With these standards a group of atoms is trapped by laser cooling and made to interact with a microwave. This method is expected to lead to a nearly tenfold increase in accuracy relative to the conventional thermal-beam method.

The most significant feature of the hydrogen maser frequency standard is that its short-term stability is extremely high relative to other atomic frequency standards. This standard is thus suited for use as a signal source for very long baseline interferometers (VLBIs) and as a signal source for atomic primary frequency standards.

Generally the hydrogen maser is large and heavy, as it consists of a microwave cavity for maser oscillation, a vacuum pumping system, and a hydrogen source, in addition to other components.

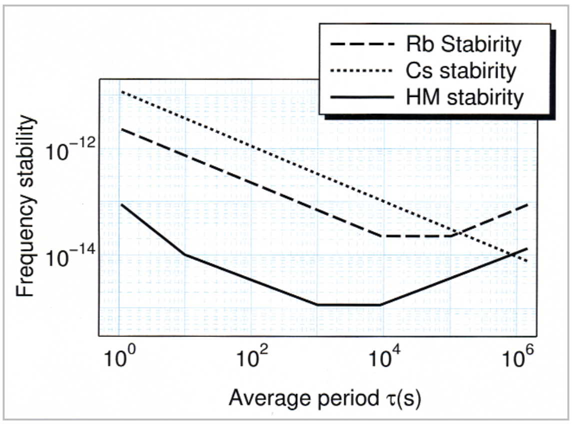

Fig.1 Stability of atomic frequency standard

1.3 Development of space-borne hydrogen maser

The first global positioning system, or GPS, was originally developed for military purposes, but today has found extremely wide applications: in automobile navigation, civil engineering, construction surveying, oil exploration, logistics of taxi and truck operations, air traffic control, prediction of earthquakes, GPS meteorology, and much more. Thus, the GPS today forms an essential part of the infrastructure indispensable to modern society, with its fields of application rapidly expanding throughout a wide range of markets. Nevertheless, Japan's global positioning applications depend entirely on the U.S. GPS; the nation has as yet not developed any of its own technologies.

This has been presented as a problem, in that Japan depends entirely on another country for such an important system. Recently demands have increased for Japan to develop its own global positioning technologies. In this context the Satellite Positioning Technology Working Group of the Space Activities Commission submitted a report entitled "Guidelines for Satellite Positioning Technology Development in Japan" in 1997, recommending that our country establish the basic technologies of a global positioning system in the short term, to be tested with a recommended minimum number of satellites.

The report enumerated the following three such basic technologies: (1) technology for a space-borne atomic frequency standard, (2) time control technology for an ensemble of satellites, and (3) highly precise satellite orbit-determining technology. Based on this report, the Communications Research Laboratory (CRL) and the National Space Development Agency of Japan have begun related research. In particular, in connection with the space-borne atomic frequency standard, the CRL has been developing space-borne hydrogen masers (SHM) in collaboration with Anritsu Corporation, based on research and development[1][2] since fiscal 1997.

Space-borne specifications present numerous technological problems, such as harsh temperatures and severe mechanical vibration at launch. As a result, hydrogen masers have yet to be subject to operations in space (with the exception of a rocket-based ballistic flight [5] performed in the 1970s to detect gravity shift). However, recently Europe and America have begun to develop SHMs for scientific applications such as space VLBIs and verification of the general theory of relativity, as well as applications in next-generation satellite positioning systems and space stations [6].

2 Principle and construction

2.1 Principle and construction

The basic construction of the hydrogen maser is shown in Fig.2. First, hydrogen gas from a hydrogen source is controlled by a device to maintain a constant flow rate; molecules of the gas are then dissociated into atoms by high-frequency electric discharge. The hydrogen atoms are given directivity by a collimator, and are emitted into a vacuum as an atomic beam. Only the atoms in the upper level are required for maser oscillation; these are selected via a level-selecting magnet and are ejected toward a microwave cavity. Hydrogen atoms remain in a storage space within the cavity for approximately 1 sec. During this period, each atom performing a transition to a lower level emits electromagnetic wave energy of 1.42 GHz, generating maser oscillation. An external VCXO is phase-locked to this signal to create a standard frequency. This summarizes the basic principle of the hydrogen maser.

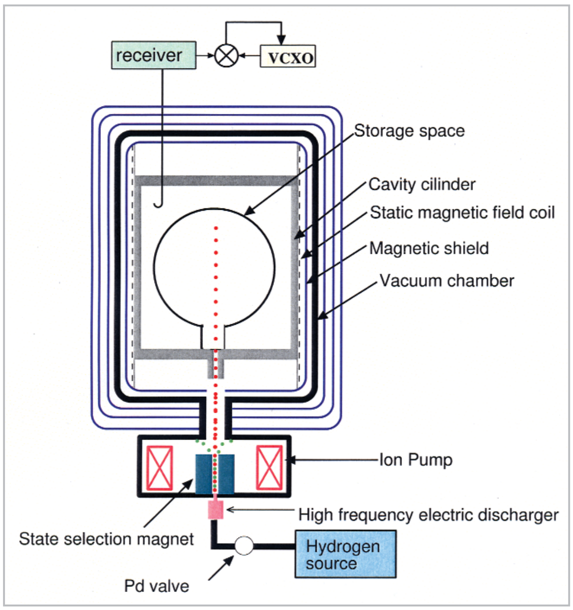

Fig.2 Structural drawing of hydrogen maser

2.2 Frequency fluctuation factors

Since the oscillation frequency of the hydrogen maser f_m may fluctuate due to various physical factors, in order to attain sufficient frequency stability, these fluctuation factors must be taken into consideration in design. The fluctuation factors of f_m include those that originate from noise (and are thus random) and those that are systematic. The latter factors will be considered here. f_m is expressed by the following formula.

$$f_m - f_H = \frac{Q_c}{Q_l}(f_c - f_H) \tag{1}$$

In the formula, f_H is the transition frequency of the hydrogen atom, f_c is the frequency of the microwave cavity, Q_c is the loaded quality factor of the microwave cavity, and Q_l is the spectrum line quality factor of the maser oscillation. Therefore, as fluctuation factors of f_m, variations in f_c, f_H, Q_c, Q_l should be taken into consideration, while variations in Q_c,Q_l are sufficiently small and need not be considered here.

Since fluctuation of f_c causes fluctuation of f_m, as seen in formula (1), high stability is required for f_c. Usually, Q_c and Q_l are approximately $Q_c \sim 40{,}000$, $Q_l \sim 1\times 10^9$, and it is necessary to satisfy $df_c/f_c < 2.5\times 10^{-11}$ ($df_c < 0.04Hz$) in order to achieve a frequency stability of 1×10^{-15}.

The most significant fluctuation factors of f_c consist of cavity deformation caused by a change in cavity temperature T_c and variation in the dielectric constant of the storage valve. df_c/dT_c depends on a variety of variables, including the structure of the cavity, the coefficient of thermal expansion of materials, and the temperature coefficient of the dielectric constant of the valve material. df_c/dT_c of a normal full-size cavity having a TE_{011} mode is $-1 \sim -0.3 kHz/K$. In order to set $df_c < 0.04Hz$, it is necessary to satisfy $dT_c < 4\times 10^{-5} \sim 1.3\times 10^{-4} K$, which requires severe temperature control.

Major shift factors of f_H include the second-order Zeeman shift, the spin exchange shift, the second-order Doppler shift, and the wall shift. If any one of these factors is subject to variation, f_m will vary. Thus, stabilizing these shift factors is essential in attaining a high degree of frequency stability.

In order to resolve the degeneration of the energy levels of the hydrogen atom, a constant static magnetic field is applied. f_H shifts according to the static magnetic field, as expressed by the following formula (second-order Zeeman shift).

$$f_H = f_{H0}(1 + 195B_c^2) \tag{2}$$

Here, f_{H0} is the transition frequency when $B_c = 0$, and B_c is the flux density of the static magnetic field, expressed in units of T. The change in transition frequency df_H when B_c changes by dB_c is expressed by the following formula.

$$\frac{df_H}{f_{H0}} = 390B_c dB_c \tag{3}$$

The hydrogen maser is operated with B_c set to $0.1\mu T$. In order to control df_H / f_{H0} to be 1×10^{-15}, the following conditions must be satisfied, in accordance with formula (3).

$$dB_c < 2.6\times10^{-11}T \tag{4}$$

$$\frac{dB_c}{B_c} < 260ppm\ (@B_c = 10^{-7}T) \tag{5}$$

There are two fluctuation factors of B_c: temperature variation of the current source for the static magnetic field coil, and variation in the external magnetic field. The former can be made sufficiently small, as the temperature stability of recent DA converters is approximately $\pm10\,ppm$ or better.

Collision of hydrogen atoms in the storage valve shifts f_H, as expressed by the following formula.

$$\Delta f_H = \frac{\lambda' h v_r}{16\pi\mu_0\mu_B^2 h' Q_c}\frac{1}{T_{20}} + \frac{q}{T_t}\frac{I}{I_{th}} \tag{6}$$

Here, λ' is the spin exchange frequency shift cross-section ($4.1\times10^{-20}m^2$), h is Planck's constant, v_r is the mean relative velocity of hydrogen atoms, μ_0 is the permeability in vacuum, μ_B is the Bohr magneton, T_{20} is the transverse relaxation time constant when the hydrogen atomic beam has a value of zero, q is the oscillation quality factor of the hydrogen maser, I is the intensity of the hydrogen atomic beam, and I_{th} is the intensity of the threshold beam. Δf_H is on the order of 10^{-13}. In order to obtain a frequency stability of 10^{-15}, it is necessary to maintain the variation in I at 1% or less.

The second-order Doppler shift and the wall shift depend on storage valve temperature. All that is required to attain a frequency stability of 1×10^{-15} is to stabilize the storage valve temperature at about 0.01K for both shifts. Since the cavity temperature is generally controlled with a stability of 10^{-4}°C or less, neither of these effects poses a problem.

As described above, the frequency fluctuation factors for a hydrogen maser differ in nature, and thus stabilization measures must be tailored to each individual fluctuation factor.

2.3 Purpose and function of each part

The operation of an atomic frequency standard principally entails the following three stages.

(1) Preparation of particles
(2) Confinement of particles
(3) Observation of particles

First, particles are prepared to obtain a sufficient difference between the numbers of atoms at different levels in order to observe the net effect of the transition. The hydrogen maser utilizes the transition between magnetic-field-induced hyperfine levels of the ground state of a hydrogen atom; it is therefore first necessary to dissociate the hydrogen molecules to create hydrogen atoms. In turn only atoms that have transitioned to the upper hyperfine level are to be supplied to the microwave cavity. The foregoing is implemented using high-frequency discharge (to dissociate the molecule into atoms), a collimator (to create the directional atomic beam), and a level-selecting magnet (to select only atoms in the upper level).

In the next stage the particles are confined in the interaction region for a sufficiently long period, thereby causing the particles to transition, resulting in a signal with a narrow linewidth. The linewidth of the set of particles that interact with the radiation field is given by the following approximation formula.

$$W \sim \frac{1}{T_r} \tag{7}$$

Here, T_r is the average interaction time. As seen in the above equation, T_r must be lengthened to the full extent possible in order to obtain a signal with a narrow linewidth; this is done in the hydrogen maser through the confinement of particles using the storage valve.

In the observation of the particles in the final stage, an actual signal is obtained. Note that the hydrogen maser uses maser oscillation generated by induced radiation in the microwave cavity as a signal source, in contrast to the cesium frequency standard and the rubidium frequency standard. Also note that although some hydrogen masers operate passively, the present paper discusses only hydrogen masers of the active type.

3 Constructing a space-borne hydrogen maser

3.1 Required performance of a space-borne hydrogen maser

The required performance of a space-borne hydrogen maser depends greatly on the orbit of the satellite to carry it, the environment in which it operates, and the specifications of the positioning system in which it is installed. Since these specifications have yet to be defined as specific values, we have assumed the provisional values shown below in our research to establish the technologies necessary for the development of the space-borne maser. As the system takes shape, actual specifications will be determined based on the results of this research.

Table 1 *SHM specifications currently assumed*

Weight	$< 100kg$
Power consumption	$< 100W$
Environmental temperature	15~35 °C
Frequency stability	$< 3 \times 10^{-15} (@10^3 < \tau < 10^4 s)$
Magnetic field coefficient	$< 1 \times 10^{-14}$/G
Temperature coefficient	$< 3 \times 10^{-15}$/°C

3.2 Technological challenges in space deployment

Fig.3 *Breadboard model of space-borne micro hydrogen maser*

The CRL has been conducting technological development of the space-borne hydrogen maser (SHM) in collaboration with Anritsu Corporation since 1997. Specifically, to date the CRL has built a breadboard model (BBM) of the space-borne hydrogen maser and has carried out a variety of performance tests.

While the hydrogen maser features markedly superior frequency stability relative to other atomic clocks (such as rubidium and cesium clocks), as described above, it is inferior in terms of weight, size, power consumption, and others. The technology of the hydrogen maser itself has already matured, with Anritsu Corporation producing commercial models based on CRL research results[3][4], models used by major research facilities throughout Japan. However, these products are designed for use on the ground, weighing several hundred kilograms, and thus cannot be carried on satellites as they are. Therefore, when designing a space-borne hydrogen maser, miniaturization and weight reduction are of primary importance. It is also necessary to devise a structure capable of enduring the mechanical vibrations of lift-off. Furthermore, as electric power is strictly limited in space, it is essential to design a device that consumes a minimum of power.

3.3 Making the hydrogen maser small and lightweight

The most significant factor determining the dimensions of the hydrogen maser is the size of the microwave cavity. If the cavity can be reduced in size, the external bell jar and magnetic shield may in turn be reduced, and the entire hydrogen maser can be made to be small and lightweight. In the space-borne hydrogen maser, this reduction in size and weight has been achieved through the use of a sapphire-loaded dielectric cavity.

In our previous analysis we found that the frequency stability of the maser is best when the inside diameter of the cavity $2a$ is twice as large as the outside diameter of the sapphire cylinder $2b$; we also found that the ratio of the cavity heights l and a can be determined in terms of the reduction in weight of the maser, and that the optimal value of this ratio is 2. At the same time, the minimum cavity volume is determined based on the required frequency stability.

The sapphire-loaded dielectric cavity shown in Fig.4 was constructed in accordance with these requirements to be capable of securing frequency stability on the order of 10^{-15}. While conventional cavity dimensions are approximately $\phi 300 \times 300\,mm$, the dimensions of the sapphire-loaded cavity are $\phi 161.9 \times 161.9\,mm$, resulting in miniaturization of about 1/8 by volume.

Along with additional design optimization, the miniaturization of the cavity enabled miniaturization of the magnetic shield, the weight of which was reduced to 17.4 kg from 64 kg; i.e., to nearly 1/4 the original weight.

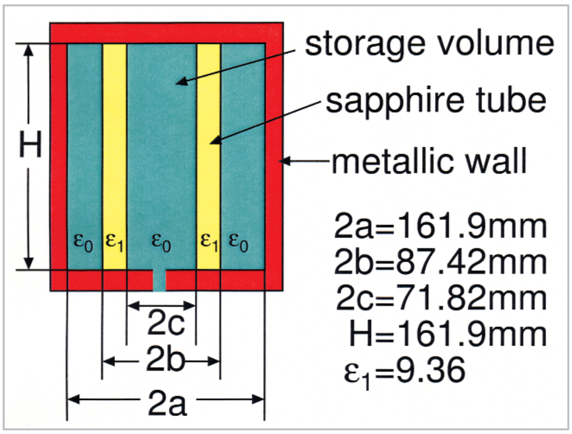

Fig.4 Structure of sapphire-loaded cavity

As further measures to promote miniaturization and reduced weight, an aluminum vacuum chamber and a getter pump (for the vacuum system) were employed, and a hydrogen storage alloy was used as a hydrogen source. This allowed for significant reduction in the weight of the trial breadboard model, to 72 kg. We are currently considering even further measures, such as the use of so-called "honeycomb" materials.

3.4 Improved protection from the space environment

A hydrogen maser to be deployed in space will operate under conditions more severe than those found on Earth. A number of protective measures should be taken into consideration, including improved temperature resistance, improved magnetic-field characteristics, improved resistance to mechanical vibration during launch, and improved operational characteristics in a vacuum.

In terms of temperature resistance, in the sapphire-loaded dielectric cavity, temperature variation in the dielectric constant of sapphire is large, df_c/dT_c reaching $-70.9\,kHz/K$. It is therefore almost impossible to stabilize f_c with temperature isolation alone; instead, stabilization of f_c by cavity auto tuning becomes indispensable.

Possible factors responsible for external magnetic-field variation include variation in the geomagnetic field and magnetic-field leakage from the magnetic gyroscope controlling satellite attitude. The variation in the geomagnetic field cannot be estimated accurately if the satellite orbit is not defined, but for purposes of illustration it can be estimated as follows: approximately $\pm 8.0 \times 10^{-7}\,T$ in the case of an orbital altitude of 20,000 km; and about $\pm 1.8 \times 10^{-5}\,T$ in the case of an orbital altitude of 3,100 km. At this time, in order to maintain dB_c at $2.6 \times 10^{-11}\,T$ or lower, it is necessary to achieve a magnetic shield factor of 62,000 or more and 1,400,000 or more, respectively.

In short, a space-borne hydrogen maser

faces environmental conditions considerably more severe than those found on the ground, and accordingly stabilization requirements are more acute.

3.5 Evaluation of characteristics

3.5.1 Frequency stability

The BBM frequency stability measurement results are shown in Fig.5. The obtained stability is worse than the targeted stability by a factor of about 2 or 3, which is attributed to influence of the frequency fluctuation caused by the temperature change described later. In this context we believe that improving the stability of the cavity temperature will result in improved frequency stability.

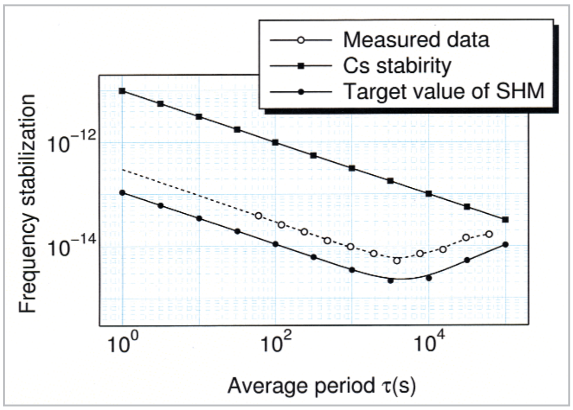

Fig.5 *Results of stability measurement*

3.5.2 Temperature characteristics

Table 2 *Measurement results of temperature characteristics*

change of frequency ($\Delta f/f$)	$3\times10^{-14}/^{\circ}C$
change of the amount of flowing hydrogen ($\Delta I/I$)	$1.4\times10^{-2}/^{\circ}C$
change of the cavity temperature	$0.02\,^{\circ}C/^{\circ}C$

The temperature characteristics were estimated by installing the BBM in a thermostatic oven, increasing the temperature of the oven from 22˚C to 23˚C, and measuring the frequency fluctuation and other characteristics as the temperature increased. As described in the previous section, in the sapphire-loaded cavity, stabilizing the hydrogen maser by automatic control of f_c is essential. This stabilization of f_c is performed by automatic, carrier-free tuning. Table 2 shows the measurement results.

The obtained temperature dependency of the frequency fluctuation is 3×10^{-14}, which is about ten times larger than the targeted value 3×10^{-15}. As seen in Table 2, the dependency of the cavity temperature on environmental temperature is 0.02˚C/˚C, ten times larger than the targeted value, which is considered to be one of the major causes of the frequency fluctuation. The following may be proposed as possible causes of the significant dependency of cavity temperature on environmental temperature.

(1) Insufficient gain in the temperature control circuit

(2) Heat-insulation performance of SHM

(3) Variation in thermo-electromotive force at connector component

We are presently investigating the actual causes so that the required improvements can be made.

3.5.3 Magnetic-field characteristics

Table 3 *Frequency fluctuation upon application of magnetic field*

Direction	change of frequency($\Delta f/f$)
x	$< 1\times10^{-14}/G$
y	$< 1\times10^{-14}/G$
z	$2.0\times10^{-14}/G$

Measurement of magnetic-field variation characteristics was performed by installing the SHM in a Helmholtz coil. The Helmholtz coil was configured such that magnetic fields can be applied independently to the x,y,z axes. The measuring time was 10 minutes, the applied magnetic fields were two different types $\pm1G$, and the measurement frequency was 1.4GHz. Automatic tuning of SHM was disabled. Table 3 shows the measurement results.

Calculation of the magnetic shield factor of SHM results in a value of 200,000. As shown in **2.2**, this is sufficient to operate the hydrogen maser regularly at an orbital altitude of 20,000km. In other words, there will be no problem when the maser is operated at normal orbital altitudes of more than 12,000 km. However, it may become necessary to increase the magnetic shield factor further, depending on the actual operational orbit.

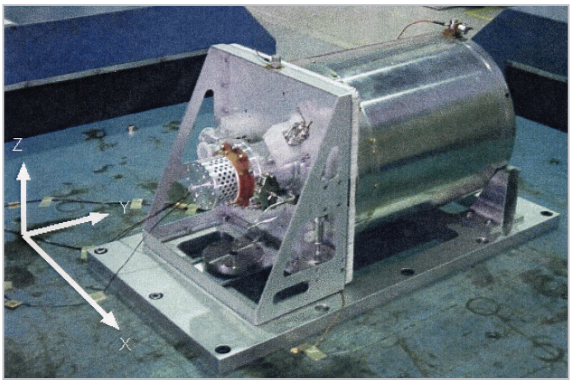

Fig.6 Configuration of vibration test

3.5.4 Vibration test

A vibration test was conducted on an experimental prototype constructed to be physically equivalent to the BBM. The experimental prototype was designed such that the vibration test could be conducted under the same conditions as those that would apply using the BBM, including factors such as weight distribution. Fig.6 shows the experimental configuration.

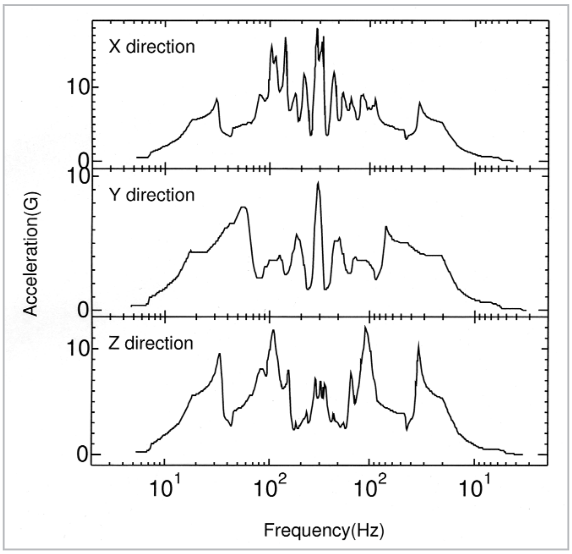

Fig.7 Results of vibration test

Measurement was performed with an acceleration of vibration of 5.0 G in a frequency range of 5 to 300 Hz. The frequency was swept upward from 5 Hz to 300 Hz in two minutes and subsequently downward from 300 Hz to 5 Hz in two minutes. Fig.7 shows the measured results and Table 4 shows the major resonant frequencies obtained, in addition to the acceleration values applied to the prototype at each resonant frequency.

Table 4 Experiment results of mechanical vibration endurance test

Acceleration	Direction	Resonances frequency(Hz)	Measured Acceleration(G)
5.0G	X	90	13.0
		110	17.0
		290	18.0
	Y	50	8.0
	Z	30	9.0
		90	12.0

Inspection of vacuum leakage and inspection of the hydrogen beam axis were conducted concurrently with the vibration test. No significant vacuum leak was observed and the deviation in the hydrogen beam axis was found to be 0.1 mm or less.

In addition, a deviation of about 100 kHz was observed in the resonant frequencies of the microwave cavity after the vibration test, which was attributed to temperature variation of the cavity.

3.6 Future challenges

Presently, the service life of the vacuum pumping system imposes a limit on the service life of the space-borne hydrogen maser. Therefore, longer operation will be possible if the hydrogen atoms can be more efficiently supplied to the storage valve. To this end we are now in the process of switching from a single collimator to a multi-collimator, modifying the design of the level-selecting magnet at the same time.

In terms of temperature variation, initial data indicated sufficient performance. However, we must conduct more detailed experiments with a view to improved operations in practical deployment.

As for the vibration test, several parts need to be redesigned to ensure that the maser is capable of enduring a vibration test at 20 G, followed by an operational test using an experimental prototype capable of actual oscillation.

4 Concluding remarks

This paper outlines the hydrogen maser atomic frequency standard, describing its basic principles and construction, sets forth the research history at the CRL, and illustrates the latest achievements in the development of the space-borne hydrogen maser.

Due to its high frequency stability, the hydrogen maser is expected to gain even wider use than seen today, most notably including expansion to new space-based applications.

The CRL has played a key role to date in the development of the hydrogen maser in Japan, and, with its current focus on deployment in space, will continue to assume a leading role in research and development well into the future.

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