

AGING, WARM-UP TIME AND RETRACE; IMPORTANT CHARACTERISTICS OF STANDARD FREQUENCY GENERATORS
(proposal for IEEE Standards, Project P1193)

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Abstract

This report is an effort to produce an IEEE standard providing guidelines for standardized methods of defining, measuring and reporting environmental sensitivities of precision frequency generators. The present report covers the subject of aging, warm-up time and retrace.

Definitions

Aging

The frequency of a typical precision frequency source may vary with time as shown in Figure 1. In the graph, a long term change of the frequency in one direction is observed after the turn on transient.

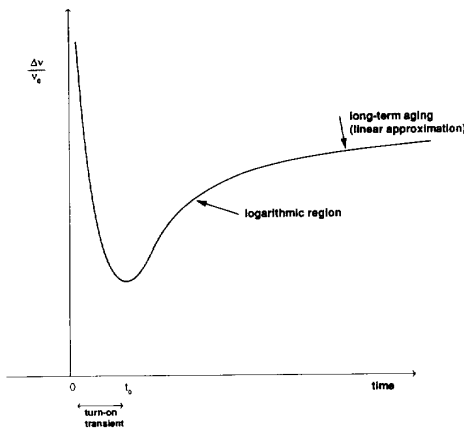


Fig. 1 Illustrations of the aging characteristic of a precision frequency source.

Shorter term fluctuations generally superimposed on the long term changes are not shown. These shorter term fluctuations may sometimes be correlated with temperature or barometric fluctuations. In such cases, their origin is known and, with adequate techniques, they can be remedied if a need is expressed. The longer term fluctuations in many cases, however, are more troublesome and it may prove to be impossible to remedy them. They may be caused for example by internal changes of the controlling element of the precision frequency source e.g. relaxation or outgassing of the quartz crystal in a quartz oscillator or the evolution of the cell in a rubidium frequency standard. In general these effects are called aging. These phenomena should be differentiated from the much broader concept of frequency drift (ref: IEEE Std 1139-1988). The frequency of an oscillator may drift with time for several reasons. For example a long term continuous change in the environment temperature may cause a long-term change in the oscillator frequency. The size of the frequency change will depend on the oscillator control element temperature sensitivity and the gain of the oscillator temperature controls. This may go on for a long period (until the temperature variations change) and, with limited measurement capability, could be mistakenly identified as "aging." We reserve the concept of aging for changes in the fundamental intrinsic properties of the control element of the oscillator, a property that characterize for example a class of oscillators fabricated by means of similar manufacturing processes. There are some areas where the distinction between aging and drift may become blurred, sometimes because of superimposed effects difficult to assess. For example a hydrogen maser's frequency may drift because of changes in its cavity frequency. If the cavity material creeps slowly with time, the frequency change observed appears as aging of the maser. However, the effect can be readily corrected by a simple re-tuning of the cavity which can be done automatically, and the "aging" disappears. On

the other hand, some bulb coatings have been known to change characteristics with time with the consequence that the maser frequency varies (ages) in a continuous fashion for very long periods of time without any ability to remedy this condition operationally. Similar discussions can be held in connection with Rb frequency standards, quartz oscillators, Cs beam frequency standards.

Consequently, we define aging as follows :

“Aging is the systematic change in frequency with time due to internal changes in the oscillator.”

This excludes frequency fluctuations caused by environmental changes as well as frequency fluctuations caused by malfunctioning oscillator components which could be improved or repaired. Aging in this context is thus a property of a type or class of oscillators and not of a defective unit in a changing environment.

Warm-up time (T_{wu})

An oscillator is characterized by various properties which are normally grouped under the form of a table. Similar oscillators are generally given the same fundamental and environmental specifications which include for example accuracy, frequency stability, temperature sensitivity, magnetic field sensitivity etc. These specifications are usually quoted for steady state operation reached only after a sufficient period of continuous operation as illustrated in Figure 2. This period is called warm up time and we simply define it as follows:

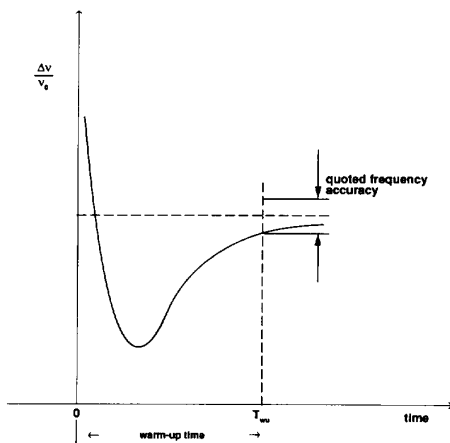


Fig. 2 Illustration of the warm-up characteristic of a precision frequency source.

“Warm-up time (T_{wu}) is the time taken by an oscillator, after turn on, to reach a steady state in which the quoted specifications are met.”

The concept “steady state” is important because of possible overshoot in the oscillator characteristics. In such a case damped oscillations may even be present in the characteristics after turn-on. Steady state may be claimed to exist only after these oscillations have decayed to a level such that specifications are continually met at subsequent times.

It is worth mentioning that warm-up depends on the environmental history of the oscillator before turn-on, in particular on its environmental temperature.

Retrace (R)

Oscillators are subject to many environmental changes of which the most drastic one is an interruption of operation called on/off operation. An important characteristic is the reproducibility of its specifications upon such a drastic environmental change. In general, for most oscillators, most specifications such as frequency stability, magnetic field sensitivity and several others will reproduce closely upon on/off cycling (after the appropriate warm-up period). However the frequency itself may be different after such an operation and to an extent that makes it clearly measurable, i.e. greater than the variation caused by its inherent frequency instability as illustrated in Figure 3.

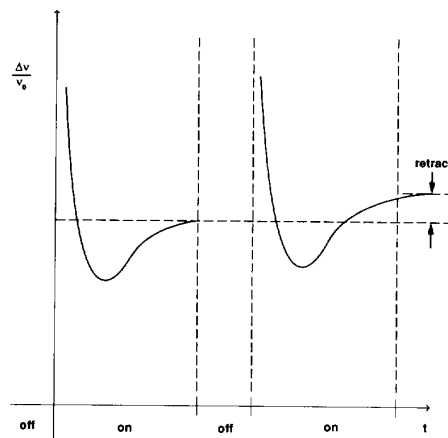


Fig. 3 Illustration of the retrace characteristic of a precision frequency source.

Thus the frequency of the oscillator is reproducible only to a certain extent during on/off operations. The following definition is given:

“Retrace (R) is the change of frequency of an oscillator after exposure to on/off operations measured after the specified warm-up time.”

This is a somewhat restrictive definition. It does not include for example other cycling operations such as on/off magnetic fields and abrupt cycling changes in temperatures. The term retrace has also been used in certain instances for characterizing other phenomena such as hysteresis in the frequency/temperature characteristics of a crystal oscillator when subjected to temperature cycling. The use of the term “retrace” is discouraged for such situations.

Formulation of a standard method of reporting Aging, Warm-Up Time and Retrace

General

1. If values are specified that apply to all individual samples of a particular type of frequency source (product specification), maximum values must be given.
2. For quantities defined here it is recommended that relative frequency be used for reporting data.

Aging

In general the long term behaviour of frequency with time of a precision frequency source is non-linear. In quartz crystal oscillators, for example, the change in frequency after turn-on may be represented by a logarithmic equation. After a period of time, characteristics of the particular source, the change may be approximated by a linear equation. In most atomic frequency standards, except may be in Rubidium standards, there is not sufficient data to conclude on a given law and thus long term behaviour is normally characterized by means of a linear equation.

a) In the logarithmic model, the frequency change is represented by:

$$\frac{\Delta v}{v_0} = A \ln (B \cdot (t - t_0) + 1) \quad (1)$$

where $\Delta v = v - v_0$, v is the frequency at time t , v_0 is the frequency at $t = t_0$, normally taken as the time at which turn-on transients have decayed to a negligible

level. A and B are determined by a least-squares fit. A has no unit and B has the unit of inverse time.

b) In the linear model, the frequency change is represented by:

$$\frac{\Delta v}{v_0} = C \cdot (t - t_0) \quad (2)$$

where C is the aging rate reported on the basis of per day, per month or per year, and is determined by a linear least-squares fit, and the other symbols are defined as above.

Effects of environmental and short term fluctuations must be removed from the specifications, i.e. they either must be controlled to be sufficiently small or they must be measured and the data correspondingly adjusted.

Warm-up Time

Warm-up time may be given in minutes, days or other units of time which appear most appropriate. The environmental temperature at which the specification applies should be given and it is assumed that the oscillator while off has reached thermal equilibrium with its environment at the time of turn on. An example for stating a warm-up time specification is:

- T_{wu} = less than 12 minutes for temperatures between -25°C and 0°C
- T_{wu} = less than 5 minutes for temperatures between 0°C and 25°C.

Retrace

If the off-time duration is not assumed to be much larger than the warm-up time it must be given as part of the specification. If the warm-up time is not given, the specification should include detailed data on the assumption made including the time of turn off and turn on. The specification should also give the range of environmental conditions which are relevant and over which retrace specifications apply if more limited than the environmental ranges otherwise specified, e.g. temperature, pressure, humidity, magnetic field intensity, etc. With the exception of aging, the unit may not move outside its retrace specification during continuous operation or discontinuous operation within the given environmental constraints. The specification should also mention if the unit is

sensitive to repetitive on/off cycling. For example, the specification could be:

Retrace or $R = \pm 5 \times 10^{-11}$ for any turn off time greater than 6 hours. (Specification applies after operating more than 4 hours). Specification applies for temperatures between -20 and $+30^{\circ}\text{C}$, barometric pressure between 50 kPa and 105 kPa and relative humidity between 20% and 65%. This statement is required when warm-up specification is not given.

Test methods

Aging

An aging measurement shall, to the greatest extent practical, avoid the effects of environmental sensitivities (such as temperature and barometric pressure), noise, and reference error. The aging data can be continuous or sampled. In the latter case, measurements shall be made often enough to resolve the true shape of the aging characteristic. Supplementary continuous data (or data taken at shorter intervals) may be necessary to establish the absence of environmental and other disturbances faster than, or synchronous with, the normal sampling interval. All measurements shall extend over sufficient time that the noise inherent in the measurements is smaller than the frequency changes to be measured (or specified) in cases where the aging is small. Measurements should start after all transient frequency changes caused by the turn-on of the oscillator have become negligible compared to the aging itself. The identity of the reference shall be stated, as well as the measurement averaging time, the measurement interval and any data averaging that is done.

The measurement of aging thus requires a) ascertaining the integrity of the frequency source and b) the stabilization of environmental parameters to levels below those which cause frequency changes of the order of magnitude of the observed aging (i.e. drift and aging must be identified).

The aging measurement shall extend over a period of time sufficient to show the intended information. The measurement of the aging of a frequency source over a certain period requires data over at least that length of time. Extrapolation shall not be used unless explicitly stated. For example, a statement that the aging rate is $3 \times 10^{-10}/\text{month}$ implies that data was taken for at least 1 month, and that this is the average linear aging over a month. It should be neither the result of only one week's

data nor the slope at the end of one month. The latter should be expressed as (say) $1 \times 10^{-11}/\text{day}$ after 30 days. Continuous operation of the source is assumed.

Comments on specific sources

Crystal Oscillators (XO): The relatively low noise and high aging of a typical crystal oscillator generally results in a well-defined fit to an aging model. The aging is usually determined by such processes as stress relaxation and redistribution of contamination that decrease with time and are often described by a logarithmic model. Some units exhibit a change in sign of aging. This is because there is more than one source of aging of opposite signs.

Rubidium Gas Cell Standards (RbFS): The relatively low aging of a typical rubidium gas cell frequency standard can easily be masked by noise or environmental sensitivities. The early aging is usually determined by such stabilization processes as Rb redistribution in the cells, and a logarithmic model may be used. The later aging is usually quite low and steady, and a linear model may be used.

Rubidium-Crystal Oscillators (RbXO): The aging of a RbXO is that of its XO during low-power operation between Rb synchronizations and that of its Rb reference during full-power operation and over the long term.

Hydrogen Masers (HM): The aging of a HM is still a question of debate. For masers with automatic or continuous tuning of their cavities, sometimes a change of wall shift, yet to be identified, causes a continuous aging. A linear model is often used.

Cesium Beam Frequency Standards (CsFS): An exceptionally stable reference and control of environmental conditions is necessary to measure the aging of these devices. The relatively high noise requires a long averaging time. In general the very low aging of a cesium beam tube frequency standard is considered to be consistent with zero.

Warm-up time

The warm-up behavior may be strongly dependent on the operating conditions, particularly environmental temperature and/or electrical supply voltage. All such factors should be considered. When the warm-up depends on temperature, the device should be allowed to soak off long enough to reach complete equilibrium.

This is particularly important for a device with a well-insulated internal oven.

The warm-up characteristics of interest can span a range of second to days (or longer). The data often takes the form of strip-chart records of such variables as input current and frequency. As a minimum, these variables should be recorded at intervals not exceeding one-tenth of the specified warm-up time.

Comments on specific sources

Crystal Oscillators: the most significant XO warm-up characteristic may be attaining/regaining a certain aging rate, and the specifications should be specific on this.

Rubidium Gas Cell Standards: The warm-up of a (RbFS) is often defined as the time to atomic lock and/or a certain absolute frequency tolerance (after prior calibration). This is generally a few minutes, and depends strongly on the environmental temperature and the supply voltage. Lockup time should be stated as the time to reach and remain in atomic lock, as indicated by a status signal. The energy required to attain a certain accuracy may be important for battery-backed applications. (This is referred to "syntonization energy" for a RbXO.) The reference point for reaching a certain frequency accuracy during warm-up is most often based on the "final" frequency—the settled value after no significant additional change takes place. The warm-up criterion is usually such that a stabilized value is quickly attained. It is unusual, however, to have a warm-up requirement related to attaining/regaining a certain aging rate.

Rubidium-Crystal Oscillators: The syntonization time and energy is critical for many RbXO applications, and the specification should be clear on this question.

Hydrogen Masers: The warm-up of a HM is ordinarily very long. Generally these devices are kept in continuous operation and warm-up conditions are not necessarily given. These devices are not designed in such a way as to optimize this parameter.

Cesium Beam Frequency Standards: The warm-up of a CsFS is usually associated with its attaining a specified frequency accuracy. All other characteristics are assumed to be reached upon warm-up unless specified otherwise.

Retrace

While the retrace requirement can involve a number of environmental and other factors, retrace, by definition, implies a return to exactly the same operating conditions. For example, a typical retrace test might involve turning a device off and on a number of times while measuring the variation in stabilized frequency. The operating conditions (temperature, supply voltage, orientation, etc) of the device should not change between runs. The test should emphasize the consistency of the retrace, and whether or not the unit shows any accumulative frequency change (trend). A sufficient number of runs should be made to show this (as opposed to fewer runs under different operating conditions). Sufficient off time should be allowed so that all internal parts of the unit reach ambient temperature. Sufficient on time should be allowed for the unit to fully restabilize.

A related factor is the on-off and/or thermal-power cycling endurance of the frequency source. This is especially important for a device such as a RbXO that is intended for many on-off cycles. A design verification test consisting of thousands of on-off and thermal power cycles may be necessary to qualify such a device.

Comments on specific sources

Crystal Oscillators: Phenomena taking place within a quartz crystal when the environment is changed (temperature, rf, power) are causes which limit the retrace. Of particular importance is the hysteresis that may be present to some extent. In general the retrace will be clearly visible over the normal aging of the oscillator.

Rubidium Gas Cell Standards: The controlling element being the atomic resonance of the rubidium gas, retrace is generally a characteristic which makes rubidium frequency standards the units of choice in some specific applications. In some types of design retrace may be of the order of the aging rate, that is barely measurable. However, in some other types of design, rubidium redistribution upon turn off, cooling and warming, may cause important changes in the characteristics of the standards with resulting measurable frequency shifts.

Rubidium-Crystal Oscillators: The retrace characteristic of the Rb reference of a RbXO is critical because, for intermittent operation, it is the retrace rather than the aging that determines the long-term stability.

Hydrogen Masers: Unless it has been turned off for a long period, the question of retrace of a hydrogen maser is normally connected to the ability to reproduce or retrace the microwave cavity. For very long periods, wall shift drift may have some importance.

Cesium Beam Frequency Standards: In general cesium beam frequency standards are used for their long-term stability and as étalons in the frequency domain. Their accuracy is given and their retrace is closely connected to their quoted accuracy.

Summary

An important characteristic of a precision frequency source or a standard frequency generator is the variation of its output frequency, caused either by internal long-term changes or alterations of operating conditions, sometimes called environmental effects. The spectrum of these changes and their causes is very large. In this report, we limit ourselves to the concept of aging, warm-up time and retrace characteristics of precision oscillators. They are examined in connection with their definition, methods of reporting their size in a given device, and techniques of measurements.

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