STRUCTURAL MODE IDENTIFICATION OF GALILEO SPACECRAFT FROM FLIGHT DATA

Che-Hang Charles Ih, Shuh-Ren I in, Edward C. Wong and Glenn A. Macala

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

Due to the noncolocation of sensors and actuator for the Galileo clock control loop, an in-flight identification was performed to identify the stator structural resonance frequencies, mode shapes and damping ratios. This information was necessary to ensure the stability of and enhance the performance of the clock controller. This Clock System identification (CLKSYSID) test was executed on-board on January 20, 1993. This paper presents the background, process, results and analysis of CLKSYSID. Some unexpected artifact modes at the multiples of 1.5 Hz showed up on the gyro rate Power Spectrum Density (PSD) plots, and the cause for that was hypothesized and demonstrated through simulation. In conclusion, the results showed that no significant stator flexible modes were excited using torque pulse inputs of various widths. Thus, no updates to the clock controller parameters were required.

1. INTRODUCTION

The Galileo spacecraft was launched in 1989 and is on its way to explore Jupiter. The dual-spin configured spacecraft will orbit Jupiter to conduct scientific investigation of the planet and its satellites. A probe will be released prior to Jupiter orbit insertion and will follow an impact trajectory for atmospheric investigation[1][2]. An illustration of the Galileo spacecraft is shown in Fig. 1.

The scan platform of the Galileo spacecraft is attached to a flexible stator structure (despun section) that is in turn attached to the rotor (spun section) of the spacecraft, “there are two degrees of freedom for controlling the inertial pointing of the scan platform. The clock actuator at the Spin Bearing Assembly (SBA) controls the relative position between the rotor and the stator, and the ccm actuator controls the relative position between the platform and the stator. The inertial sensors (gyros) are located on the platform.
The cone actuator and the gyros are separated by a rigid platform structure, hence gyro measurements can be directly used by the cone controller to generate cone actuation signals. The clock actuator, however, is separated from the gyros by the flexible stator structure. Because the sensors and actuator are noncolocated, the gyros sense flexible motion as well as rigid body motion. When the clock controller attempts to compensate the position error caused by the flexible vibration at the resonance frequencies, it may destabilize the system. Thus, a wide double-notch filter was imbedded into the clock controller design (see Fig. 2) to attenuate the control gain at the notch frequency and prevent the flexible motion from feeding back into the structure [3] [4]. However, due to the high uncertainty in the ground NAS"l'KAN model, an in-flight identification of the stator flexible mode characteristics (modal frequency, damping and coefficient) is necessary to accurately locate the “destabilizing frequencies” and identify the corresponding modal damping and mock shapes to enhance the performance of the notch filter and stabilize the platform motion [3].

The detailed description of the strategy, design, constraints, flight implementation and simulation of the CL.K SYSIII was presented in Ref. 3. This paper reviews the strategy and implementation, but focuses primarily on the results and analysis of the in-flight CL.K SYSIII.

11. IN-FLIGHT IDENTIFICATION STRATEGY AND IMPLEMENTATION

The basic approach of CL.K SYSIII is to excite the stator structure using a SBA (clock actuator) torque pulse, then collect and analyze gyro data. The CL.K SYSIII strategy and implementation issues are reviewed first in this section to facilitate the discussion of the results and analysis in the next section.

2.1 The Notch Filter and Inertial Mode Clock Controller Design

The Galileo clock controller in inertial mode (in which gyros are used for sensing) consists of a scan commander, a proportional-integral-derivative controller, and a notch filter. It is shown in Fig. 2 with the scan commander omitted. The scan commander processes pointing commands to determine the target position of the scan platform and the slew path required to reach that position. Upon receiving the scan platform attitude information, it also generates feedback position and rate errors to feed into the controller in both clock and cone axes [5]. As mentioned before, due to the noncolocation of the sensors and actuator for the clock control loop, a wide double-notch filter was added in the loop to attenuate the control system gain at the notch frequency so that the magnitude
of the resonance peaks can be reduced to levels having reasonable stability margins. The z transfer function of the double-notch filter is

\[
\frac{\text{output}(z)}{\text{input}(z)} = \left( \frac{z - e^{-\lambda T}}{z - e^{-\lambda T}} \right) \left( \frac{z - e^{-\lambda T}}{z - e^{-\lambda T}} \right)
\]

where \( \lambda \) is the resonance frequency that is to be notched out and \( T \) is the sampling period. The wide notch is used because of uncertainty in the knowledge of the resonance frequencies. This effectively widens the frequency range for gain attenuation. The double-notch approach provides twice the amount of attenuation as a single notch. The purpose of the in-flight identification of the stator structural resonance frequencies is to locate those “destabilizing frequencies” and the corresponding modal dampings and mode shapes so as to determine the proper parameter values for the notch filter.

2.2 Spacecraft Configuration

The spacecraft was put in inertial mode with the gyros on. The configuration showing the relationship between the stator (X, Y, Z) and platform (M, N, L) coordinates is shown in Fig. 3. The scan pointing performance is measured by the pointing accuracy of the instrument boresight vector (along the L axis). This pointing error is computed by the scan commander in terms of the position and rate error information about the platform cone N and cross-cone M axes. Motions about these two axes can be sensed by the gyros. Note that the N axis is aligned with the Y axis and that the L, M, X, Z axes all lie on the same plane. The L axis may be oriented by varying the cone angle \( \beta \), where \( 0 \leq \beta \leq 2100 \).

There is a variation in the observability of flexible components in the stator X and Z axes by the gyros as the cone angle \( \beta \) varies. The M axis is aligned with the X axis when \( \beta = 0^\circ \), components in the X axis are completely observable and components in the Z axis are unobservable along the M axis. For CI.KSYSID, since the measurements of interest were those about the stator Z axis (excited by clock actuator about the Z axis), \( \beta \) was set to 90° so that the M axis became aligned with the Z axis. Components in the Z axis became completely observable along the M axis. Also, since the M axis is always along the gyro 1Y and 2Y axes (see Fig. 4), if a SBA torque is introduced about the Z axis, all of the flexible motion components about the Z axis are observable in the gyro 1Y and 2Y outputs. Gyro 2Y outputs were chosen to be the primary data source for this analysis.
2.3 Excitation Torque

As mentioned before, SBA torque was used to excite the spacecraft flexible structure. A torque pulse was chosen because it was easy to implement and it resembled a torque impulse. Its frequency harmonics content enabled the excitation of flexible modes over a larger frequency range of interest. However, the SBA torque saturates at 3.8 Nm -- the software torque limiter. The only way to increase the excitation energy is to increase the torquing duration. The Power Spectrum Density (PSD) of a square pulse of width At is a function of the frequency ν (in Hz),

$$S(ν) = \frac{\sin^2(\pi ν At)}{(π ν)^2 At}$$  \hspace{1cm} (1)

and the nodes of the frequency harmonics are located at n/At Hz, n= 1, 2, 3, 4, . . . . Flexible modes located within about ± 0.1 Hz from each node can not be adequately excited. Therefore, it is essential to design an identification scheme, that is able to generate torques with variable pulse widths such that all the frequencies within the range of interest should be at least 0.1 Hz away from at least one node.

The 1-cal-time interrupts (RTI) designed for the Galileo attitude control flight software can provide various torque pulse widths which are multiples of 66 2/3 ms. Most of the attitude determination and control functions are executed once in this interval. Ten RTIs constitute a “minor frame” for telemetry. Five different pulses of varying widths (7, 8, 9, 10 and 11 RTIs) were used to ensure proper excitation of all modes within the range of interest (below 15117, the gyro rolloff frequency). Two types of commands were needed to generate a torque pulse: 7S1 L:W and 7DBS:$. The 7S1 L:W command was used to spin up the stator to -10/sec from rest which saturated the SBA software torque limiter (-3.8 Nm) instantly. The first 7DBS: was used to specify the desired pulse width. After a full torque excitation period, the second 7DBS: was used to lower the SBA saturation limit to the level that would just compensate the friction produced by the SBA slip ring. Thus, when the excitation was done, ideally there should be no net torque applied to the stator. Based on previous in-flight SBA friction torque calibration results, the compensation torque value was set to -0.4 Nm.

2.4 Telemetry Data Collection

A special mode of spacecraft telemetry, known as “flood mode” telemetry was adopted for C1.KSYSID data collection at a high sampling rate. It provides for up to six telemetry variables “every RTI (66 2/3 msec). Normally, the flood mode telemetry buffer is not part of the regular telemetry stream. To obtain the telemetry data in this mode, the buffer must be transferred to the
bulk memory in the Command Data Subsystem (CDS) once every minor frame (2/3 see) and then read out from that memory. The six telemetry channels selected were Gyro 1X, Gyro 1Y, Gyro 2X, Gyro 2Y, SBA torque, and SBA position. Each memory readout from the bulk memory contains a maximum of 38 2/3 seconds or 580 data points. As mentioned before, Gyro 2Y was the main data source for the frequency domain analysis.

2.5 Gyro Data Processing

The collected raw gyro data were position measurements (θ) along the M axis. However, it was the gyro rate which was used as the input to the ground software. The gyro rate (ω) information was obtained by [3]

\[ \omega(t_k, t_{k+1}) = \frac{\theta(t_{k+1}) - \theta(t_k)}{t_{k+1} - t_k}, \quad k = 0, 1, 2, \ldots \]

where \( t_k, t_{k+1}, t_{k+2}, \ldots \) are the gyro sampled times, and \( t_{k+1} - t_k \) is constant for all values of \( k \) (66 2/3 msec, or 1 RTT) during the period the gyro samples are collected.

2.6 Ground Software and Identification Strategy

Two ground software programs -- CLKAID and PAR AID were developed to analyze the gyro rate data. The first program, CLKAID, simply generates the PSD of the gyro rate signal. The user then identifies the "peaks" in this waveform and thereby determines the modal frequencies of the stator structure. The second program, PAR AID, establishes a dynamical model of the stator structure in the clock control loop that includes all of the modal characteristics of the expected flexible modes below 15 Hz. The model consists of a transfer function of \( N \) flexible modes in the form

\[ T(s) = \sum_{i=1}^{N} \frac{C_i}{s^2 + 2\zeta_i\lambda_i s + \lambda_i^2} \]

where the unknowns to be identified are: \( C_i \), modal coefficients, \( \zeta_i \), modal damping factors, and \( \lambda_i \), modal frequencies. \( N \) is number of modes with resonance frequency below the gyro rolloff frequency (15 Hz). The shape of the PSD centered at a modal frequency is a function of the modal coefficient \( C \) and damping factor \( \zeta \). The relation can be easily described by considering a structural response (to a square torque pulse) to be a damped sinusoidal function of the form,

\[ f(t) = ce^{-\zeta \lambda t} \sin \lambda t \]
where \( A \) is the resonance frequency. The Fourier transform of \( f(t) \) is approximately

\[
g(\omega) = \frac{c}{2} \left[ \frac{1}{\omega - \lambda - i\zeta \lambda} \right]
\]

for frequency \( \omega \approx \lambda \) and \( \zeta \ll 1 \). The PSD of \( f(t) \) is \( |g(\omega)|^2 \), which is proportional to

\[
|g(\omega)|^2 \propto \frac{c^2}{(\omega - \lambda)^2 + (\zeta \omega)^2}
\]

It is clear that \( c^2 \) affects the magnitude of \( |g(\omega)|^2 \) proportionally, while the magnitude (height) of \( |g(\omega)|^2 \) is only sensitive to the variation of \( \zeta \) when the frequency is near \( 1 \). However, \( |g(\omega)|^2 \) becomes rather insensitive to \( \zeta \) when \( \omega \) moves away from \( \lambda \), since \((\zeta \lambda)^2\) will become negligible compared with \((\omega - \lambda)^2\). By applying the identical excitation torque as in-flight and feeding the modal frequencies identified from \( \text{Cl.KTDA} \) into this model, \( \text{PARAID} \) will adjust the modal coefficient and damping factor for each mock such that the PSD of the model output matches the PSD of the telemetry data, in frequency and amplitude, to some satisfactory accuracy. "The identification strategy is illustrated in Fig. 5."

### 11. RESULTS AND ANALYSIS

#### 3.1 Cl.K SYSID Results

As mentioned in Subsection 2.3, there were five test cases corresponding to the five excitation torques with pulse widths of 7, 8, 9, 10 and 11 R". The SBA excitation torque and the resulting gyro 2Y rate time histories for each case are shown in Figs. 6-10. Part (b) of each figure -- a close-up of the excitation torque at the RT1 level, the excitation torques for each case are exactly as designed. As mentioned before, the compensation torque value after excitation was set to -0.4 Nm based on previous SBA friction torque calibration results. However, as can be seen from Figs. 6-10, this compensation torque did not cancel the average friction torque exactly. SBA calibration on January 21, 1993 (a day after Cl.KSYSID) showed that average SBA friction torque was about -0.33 Nm. The effect of the residual torque is that after the excitation is done, the gyro rates gradually increase instead of holding constant, as clearly shown in Figs. 6-10. Whether the non-constant gyro rates can cause adverse effect on the Cl.KSYSID result or not is discussed later in this section.

The first ground software program Cl.KTDA was then run to generate the PSDs of the Gyro 2Y rates for each case. In addition to this, the MATLAB function `spectrum.m` was also used to
generate those PSDS. The purpose of doing so is twofold. One is to double check the \texttt{CLKTDA} results. The other is to facilitate further analysis using \texttt{MATLAB} on a SUN workstation since \texttt{CLKTDA} is written in FORTRAN and resides on a UNIVAC mainframe. This point will become clear as we proceed. The PSDs of the Gyro 2Y rates using \texttt{CLKTDA} and \texttt{spectrum.m} are shown in Figs. 11-15 for the 7-11 RTJ excitation cases, respectively. The results obtained using these two programs are very similar. In general, the PSDs generated by \texttt{spectrum.m} are about an order of magnitude higher than those generated by \texttt{CLKTDA}. This suggested that very likely the scaling factors used in these two programs were different. However, the most important fact is that the locations of the peaks (frequencies) are the same, and the relative amplitudes between the peaks are very close. Based on these plots, peaks at 1.5, 3, 4.5 and 6 Hz were identified. The fact that these frequencies are multiples of 1.5 Hz (minor frame data rate) makes them suspicious as to whether they are indeed the real structural modes. Further investigation revealed that these frequencies fall right on the nodes of the PSD of the 10 RTJ excitation torque square pulse (see Eq. (1)), Hence, for this 10-RTJ excitation case, no mode should be excited at all at these nodes. However, they did show up on Fig. 14. Therefore, it is confirmed that these peaks are “artifact modes”, not real structure modes.

3.2 Analysis Through Simulation

To investigate where these artifact modes came from and why no structural modes were evident, a simple dynamic model (Fig. 16) consisting of the rigid body as well as two flexible modes and a gyro model (Fig. 17) was developed and a series of simulations were conducted using \texttt{SIMULINK}. The flexible modes selected were the two dominant modes used in the simulations in Ref. 3. They were the dominant modes in an older version of the ground mock. However, for this simulation, the modal damping $\zeta$ was set to 0.25\% for both modes instead of 0.34\% and 0.23\% as in Ref. 3. To summarize, the modal characteristics of these two modes are:

<table>
<thead>
<tr>
<th>Modal Frequency $\lambda_i / 271$ (Hz)</th>
<th>Modal Coefficient $c_i$</th>
<th>Modal Damping $\zeta_i$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.43</td>
<td>$-6.594 \times 10^{-3}$</td>
<td>0.25</td>
</tr>
<tr>
<td>9.31</td>
<td>$-5.966 \times 10^{-3}$</td>
<td>0.25</td>
</tr>
</tbody>
</table>

The Bode magnitude plot of the system is shown in Fig. 18. The two peaks confirm that the dominant modes are indeed located at 8.43 and 9.31 Hz. The same 10 RT1SBA excitation torque was injected into the system with a 0.05 Nm residual torque following the completion of the excitation, as shown in Fig. 19. The gyro position data were then collected and processed to generate gyro rate in exactly the same way the flight data were processed. The simulated gyro
position and rate time histories are shown in Fig. 20. Comparing Fig. 9(c) and Fig. 20(b), it can be seen how close the real and the simulated gyro rates are for the 10 RTI excitation case, indicating that the imperfect compensation of SBA friction torque was truthfully emulated. MATLAB function spectrum.m was then used to generate the PSD of the resulting gyro rates, as shown in Fig. 21. The two modes excited were at about 5.7 Hz and 6.6 Hz, the aliased modes of the 9.31 Hz and 8.43 Hz modes seeded in the model (about the Nyquist Frequency 7.5 Hz, half of the sampling rate). It is interesting to note that no artifact modes were observed, revealing that the imperfect compensation of the SBA friction (thus the non-constant gyro rate after the excitation) had nothing to do with the artifact modes.

It was hypothesized that the most possible cause of the artifact modes was the I/O timing error. The gyro data appearing in the telemetry were the gyro position data. Ideally every 10 RTI (1 minor frame, 2/3 sec) CDS reads the last 10 data points into CDS memory, then commands are issued to read out the CDS memory. However, the timing of this process on-board may not be perfect. If CDS reads the data a little earlier or a little later than exactly one minor frame, it will result in errors when the gyro rate is calculated by the ground software, and an artifact effect may occur. To emulate this situation, 6 micro radians was added to the gyro position data at RTI1 of the minor frame and subtracted out at RTI2. A random number generator and an index were used to control the probability with which the above-mentioned imperfect timing occurs. The probability was varied from 30%, 50%, 70% to 100% in the simulations. For each case, PSDs of the gyro rates were generated using spectrum.m and plotted in Fig. 22. It can be seen that as the probability of imperfect timing increases, the artifact modes of 1.5 Hz, 3 Hz, 4.5 Hz, and 6 Hz become more and more evident. The important finding, however, is that the real modes are essentially unaffected as compared with those in Fig. 21. Hence, it is concluded that if any flexible modes were excited by the applied SBA torque, they would not be “buried” due to the existence of artifact modes.

Since the Low Gain Antenna (LGA) swing test for the High Gain Antenna (HGA) anomaly investigation found that the damping of the spacecraft’s flexible modes was much higher than expected (some of them as high as 2%) [7], another simulation was run by setting the damping of the two dominant modes in the SIMULINK model to 2% with no artifact effect. The resulting gyro rate PSD is shown in Fig. 23. The two modes almost disappeared as compared with those in Fig. 21 (0.25% damping). By repotting Fig. 14(b) (the in-flight 10 RTI excitation case) using the same scale of Figs. 21-23 and omitting the artifact modes, the resulting plot (Fig. 24) is extremely close to that of the 2% damping case (Fig. 23). Comparing with the two modes in Fig. 21, they are both clearly in the noise level. This indicates that higher damping could very possibly be the cause
of the absence of true modes on the PSD plots. Since no significant modes were identified, it was not necessary to run the second ground software PARAID.

IV. CONCLUSIONS

After Galileo’s flight data was processed using the CLK SYSID ground software, no prominent stator flexible modes were identified, Artifact modes with frequencies at multiples of 1.5 Hz (minor frame data rate) showed up instead. Simulations demonstrated that these artifact modes could possibly be due to on-board data I/O timing error. The leading explanation for the absence of any true structural modes is that the damping of the flexible modes was higher than expected, and therefore, true stator modes simply could not be excited by the torques applied. In any event, the flexibility of the stator presents no adverse effect to the stability and performance of the clock controller, thus none of the clock controller parameters need to be updated.

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REFERENCES

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(b) MATLAB Function Spectrum Result

Frequency (Hz)

Psd for Gyro 2Y Rate 10 RTI No Rigid Body Mode

(a) Ground Software CIKIDA Result

Frequency (Hz)
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(a) 30% Probability of Imperfect Timing

(b) 50% Probability of imperfect Timing

(c) 70% Probability of Imperfect Timing

(d) 100% Probability of Imperfect Timing

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