A NEW CHALLENGE IN ROBUST CONTROL OF THE ADVANCED SOLID ROCKET LAUNCHER

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ABSTRACT
The development of the Epsilon launch vehicle, Japan’s next generation solid rocket launcher, has just moved on to the final stretch for its first launch scheduled in summer of 2013 carrying the planetary telescope satellite SPRINT-A. It should be emphasized that the JAXA appreciates the advantages of combined power of the standardized small satellites and the Epsilon’s highly efficient launch system to increase the level of space activities. The novel concept of the vehicle, aimed at achieving the next generation space transportation technologies, requires a simpler launch system and better user friendly interface than its predecessor, M-V in order to provide small satellites with more versatile launch. Such innovation significantly affects the architecture of the attitude control system of the vehicle, which should be more robust and reliable. This paper describes the design of the attitude control strategy of the Epsilon launcher.

KEY WORDS
Robust control, Guidance and control, Control theory, Attitude control.

1. Introduction
The research on Japan’s solid rockets started more than 50 years ago with a horizontal launch experiment of tiny pencil-size rockets and such endeavor was rewarded in 1970 when Japan’s first satellite “Ohsumi” was launched and in 1985 Japan’s first planetary spacecraft “Sakigake” was lifted toward Halley’s comet. In mid-90’s, the M-V rocket became available to meet the strong demand for the full scale scientific missions including the world’s first asteroid sample-return spacecraft “HAYABUSA” that returned home safely in 2010. In 2006, the M-V also launched the infra-red space telescope “AKARI: at that moment, it became the world’s best performance solid rocket launcher that can be utilized for both planetary and sun-synchronous missions. In addition, it cannot be forgotten that from the very beginning Japan’s research on solid rockets has been conducted independently of foreign technologies: a source of Japanese pride. In this way, the space science communities of Japan have for its first flight in summer of 2013 to launch the space telescope satellite SPRINT-A.

Note that the background of the Epsilon is based on the achievement of the M-V. First of all, the M-V contributed to space science in almost all its fields from the space astronomy to even the planetary missions (Figure 2). Back in 2003, the M-V launched the world’s first asteroid sample-return spacecraft “HAYABUSA” that returned home safely in 2010. In 2006, the M-V also launched the infra-red space telescope “AKARI: at that moment, it became the world’s best performance solid rocket launcher that can be utilized for both planetary and sun-synchronous missions. In addition, it cannot be forgotten that from the very beginning Japan’s research on solid rockets has been conducted independently of foreign technologies: a source of Japanese pride. In this way, the space science communities of Japan have

Figure 1. Epsilon rocket launcher on pad.
obtained series of world-leading achievements by using the M-V; however, they suffered from the relatively low launch frequency mainly due to the relatively high cost and the long development period of those full scale scientific missions: only 7 spacecraft in 10 years. The space science will not survive in this situation, thus they now focus on more satellites smaller in size, lower in cost and shorter in development period in order to increase the launch opportunities.

With this as background, the purpose of the Epsilon rocket is to provide small satellites with responsive launch, which means in the study we focus on a low cost, user-friendly and ultimately efficient launch system (Figure 3). The combined power of small satellites and the small launcher will increase the level of space activities. Throughout 50 years history of Japan’s solid rockets, the research was conducted only to increase the rocket performance. Now, for the first time ever in the history, it requires optimization of the entire launch system. This attempt is equally applicable to the liquid rockets as well and paves the way to future space transportation systems.

Then what is the largest revolution we aim at for the Epsilon? That is the innovative launch system to reform the old-fashioned launch system into an ultimately efficient one. The key to success is avionics systems: they are designed to be highly intelligent so that the vehicle performs check-outs autonomously and to be connected to the ground support facilities, through a high-speed network. Owing to this endeavor, lots of ground support equipments can be all eliminated and the associated set-up time and the number of personnel involved can be reduced. Until now, the launch control room contains tons of ground support equipments and lots of workers involved. From now on, the intelligent check-out system and the secured high-speed network makes it possible to conduct the launch control anytime, anywhere in the world simply by using a single laptop computer, which is called a mobile launch control, a realization of the science fiction to the science fact (Figure 4). The concept of the vehicle, the next generation launch system, requires simpler launch system and better user friendliness than its predecessor, the M-V in order to provide small satellites with an efficient launch. From the point of view of the astrodynamics, such innovation significantly affects the architecture of the guidance and control system. This paper describes a challenge in control design of the Epsilon rocket launcher.

2. Hardware Architecture

The configuration of the Epsilon rocket is a three-staged solid propellant vehicle, having a 1.2-ton payload capacity into a low earth orbit (LEO) while it is 92 ton in lift-off weight, 24 m in total length, and 2.5 m in maximum diameter (Table 1). Each of the first and the second stages has 3-axis attitude control capability (Figure 5): the pitch and yaw in the powered flight can be controlled through a mobile nozzle thrust vector control (MNTVC) that are driven by a pair of electro-mechanical servo-motors. The first stage servo-motor is powered by a special high power thermal battery and the second through an integration of commercial lithium batteries. On the other hand, the roll in the same phase and the 3-axis attitude in the coasting phase can be stabilized by reaction jets. The first stage reaction jet, solid motor side jet (SMSJ), is generated by a solid propellant gas generator (GG) while the one for the second stage, reaction control system (RCS) by conventional hydrazine engines.

Contrary to the M-V, the third stage is just spin-stabilized for more simplicity. To compensate for the
residual orbit error caused by the spin-stabilized third stage, an optional tiny upper stage, post-boost stage (PBS) can be installed onboard, which will be propelled by conventional hydrazine engines (Figure 6). This is for better orbital accuracy and maneuverability to increase the user friendliness. To further enhance the user-friendly characteristics, a special payload attach fitting (PAF) is under development to lower the level of high frequency vibration (around 50 Hz) that is caused by the combustion vibration of the first stage solid rocket booster (SRB-A). The mechanism of the vibration attenuator consists of a multi-layered structure of rubbers and thin metals, having lower axial rigidity, to isolate the high frequency vibration (Figure 7). The structure also causes a reduction in the lateral rigidity of PAF, resulting in lower bending frequency of the entire vehicle. This is absolutely a new challenge for the attitude control algorithm design because the rigid mode dynamics and the first order bending oscillation will become much closer.

Table 1
Specifications of the Epsilon rocket (EX)
*E1 denotes the upgraded version of Epsilon that aims at lower cost character and is planned to be developed after the current version (EX).

<table>
<thead>
<tr>
<th>Items</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration</td>
<td>3-stage solid propellant launcher with optional PBS</td>
</tr>
<tr>
<td>Length/Diameter</td>
<td>24 m/ 2.5 m</td>
</tr>
<tr>
<td>Lift-off mass</td>
<td>92 ton</td>
</tr>
<tr>
<td>Launch Capacity</td>
<td>LEO (250×500 km): 1.2 ton SSO (500 km): 450 kg (550 kg for E1)</td>
</tr>
<tr>
<td>Cost per launch</td>
<td>¥3.8 billion (US$49M*)</td>
</tr>
<tr>
<td></td>
<td>&lt; ¥3.0 billion for E1 (US$39M*)</td>
</tr>
<tr>
<td>Next Generation</td>
<td>Autonomous Checkout System</td>
</tr>
<tr>
<td>Technologies</td>
<td>Mobile Launch Control</td>
</tr>
<tr>
<td>Development Cost</td>
<td>¥20.9 billion (US$271M*)</td>
</tr>
<tr>
<td>First Flight</td>
<td>in 2013 (E1 in 2017)</td>
</tr>
<tr>
<td>Launch Site</td>
<td>Uchinoura Space Center (USC)</td>
</tr>
</tbody>
</table>

3. Attitude Control Algorithm Design

The design algorithm of the attitude control applied to Japan’s solid rocket launchers has evolved since mid 80s which is featured by its step-by-step enhancement of robustness character (Table 2). Note that despite the classical design methods are still adopted worldwide for the launcher control, the modern and post-modern design architectures were successfully applied to Japan’s solid rockets to get better robust characteristics against variations in the plant dynamics: the entire system has a grade of uncertainty of system parameters. Especially, the $H_\infty$ control theory was applied to the first three flights of the M-V (1997-2000)\(^{1-3}\). Within the framework of a mixed sensitivity problem, the challenge is to achieve better tracking performance in a relatively low frequency region as well as preferable robust stability in the high frequency range: nominal performance and robust stability. Beyond this success, the further novel design was taken to renew the attitude control of the last four flights of M-V (2003-2006), which utilizes the more advanced $\mu$-synthesis to enhance the system’s tracking performance more directly\(^{6-14}\). The $\mu$-synthesis was applied for the first time ever in the world for the satellite launcher control beyond the reliable $H_\infty$ control to get far better robust characteristics not only in stability but in tracking performance. In sharp contrast to the $H_\infty$ design, the $\mu$-synthesis can treat the robustness directly even in the performance. In this way, the robust control design of
the M-V launch vehicle evolved since its first flight in 1997 using $H_\infty$ theory through its last journey in 2006 applying the $\mu$-synthesis. Basically the same advanced approach is applied to the Epsilon rocket launcher.

### 3.1 Established Robust Control Design Approach

The design procedure that was established for the M-V rocket is summarized in this section. First of all, the essential task of the control algorithm is to obtain measurement of the attitude angle and its velocity from the sensing device, the gyro, and issue the driving command to the actuating system, the mobile nozzle. Due to the limited availability of the associated information, the attitude control logic takes a form of dynamic output feedback compensation as:

$$\dot{z} = Ac z + Bc (y - r);$$  
$$u = Cc z + Dc (y - r).$$  

(1)

The controller was allowed only 6 states maximum due to the limited capacity of the onboard processing unit for the M-V while it is increased to 10 for Epsilon. The design target is to get preferable tracking performance in a low frequency region as well as robust stability in a relatively higher. The requirement of stability margin is specified to the nominal plant model; gain margin of 6 dB; and phase margin of 20 deg. In addition, the controller is required to guarantee robust stability against uncertainties of the system parameters. As to the tracking performance, the requirement can be specified only to the nominal plant model for the $H_\infty$ design while $\mu$-synthesis can accommodate deviated plant dynamics as well for better characteristics.

As to the plant dynamics involving the attitude motion, the bending deformations, the mobile nozzle’s dynamics and sensor’s characteristic, the total number of states is 25 for the second stage flight and it is considered relatively high to treat within the framework of the mixed sensitivity problem. For easier derivation of a controller, the order is reduced to 22 by exclusion of the 3rd order sensor’s dynamics, which is much higher than the rest of the entire dynamics. This leads to the following reduced expression of the governing equations of motion:

$$\dot{x} = A_r x + B_r (u + d);$$  
$$y = C_r x + w.$$  

(2)

It should be strongly emphasized that the reduced dynamics still involves relatively high order character while it remains unstable in the rigid body dynamics. Note that in the D-K iteration, utilized for the $\mu$-synthesis, the first $H_\infty$ design is required to stabilize the plant dynamics. However, the standard process to derive the first one is practically ineffective due to the plant’s high order character and its instability. Hence, in the design strategy taken here, the standard procedure is modified in a special way to make it more efficient. This is featured by pre-stabilization of the plant dynamics: a local measurement feedback is installed to preliminarily stabilize the original unstable plant dynamics as follows:

$$u' = D_{cp} C_r x_r.$$  

(3)

Then the stabilized plant, to which the standard procedure is applied, can be represented by the following expanded expression as:

$$\dot{x} = (A_r + B_r D_{cp} C_r ) x + B_r (v + d);$$  
$$y = C_r x + w.$$  

(4)

Here, $v$ denotes the new control output to be designed by the standard $\mu$-synthesis. With the plant dynamics in hand, the next logical step is a selection of the weighting functions: the most important and difficult task in the mission. In the study, the weighting function on robust stability is taken to involve a combined structure of phase lead and lag elements; and a 2nd-order system, having the 4-th order character in total while the one for performance is a simple second-order system as:

$$W_{\delta r} = \frac{s^2 + 0.1 s + 1}{s^2 + 0.001 s + 1};$$  
$$W_{\delta} = \frac{s}{s^2 + 0.1 s + 1}.$$  

(5)

Now, the standard $\mu$-synthesis design routine is directly applied to the pre-stabilized plant dynamics along with the weighting functions specified above, which yields the dynamics of the controller as:

$$\dot{z} = Ac z + Bc (y - r);$$  
$$v = Cc z + Dch (y - r).$$  

(6)

Then, the entire controller that should be utilized for the original unstable plant dynamics can be provided by the combination with the prescribed feedback gain as:

$$\dot{z} = Ac z + Bc (y - r);$$  
$$u = Cc z + (Dc + Dch)(y - r) + D_{cp} C_r x_r.$$  

(7)

Note that the input to the local feedback is augmented to $y - r$ in this conversion. The performance of the controller is checked against the entire group of deviated models in their original unstable plant configuration: the stability survey in frequency domain and the time-domain

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**Table 2**


<table>
<thead>
<tr>
<th>Rocket</th>
<th>Design</th>
<th>Robust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Launch No.</td>
<td>format</td>
<td>stability</td>
</tr>
<tr>
<td>M-V-1 (1997)</td>
<td>$H_\infty$</td>
<td>Yes</td>
</tr>
<tr>
<td>M-V-3 (1998)</td>
<td>$H_\infty$</td>
<td>Yes</td>
</tr>
<tr>
<td>M-V-5 (2003)</td>
<td>$\mu$</td>
<td>Yes</td>
</tr>
<tr>
<td>M-V-6 (2005)</td>
<td>$\mu$</td>
<td>Yes</td>
</tr>
<tr>
<td>M-V-8 (2006)</td>
<td>$\mu$</td>
<td>Yes</td>
</tr>
<tr>
<td>M-V-7 (2006)</td>
<td>$\mu$</td>
<td>Yes</td>
</tr>
</tbody>
</table>
performance check by nonlinear, time-varying numerical simulation. When the required level cannot be achieved, the pre-specified feedback gains and the weighting functions will be changed to resume the procedure. It should be emphasized here that due to the transformation of the plant dynamics, the selected weighting functions do not directly correspond to the original unstable system. Thus, pre-stabilizing feedback gains and the parameters of weighting functions for the pre-stabilized system have to be carefully chosen so as to guarantee preferable control performance for the original plant model. This is the most important task in the procedure, which involves some trial-and-error type effort but is quite straightforward. The final attention should be directed toward the fact that the order of the designed controller is equivalent to the sum of that of the original plant and those of the associated weighting functions, thus amounting to 28. It is reduced to the allowed while maintaining distortion of the $H_\infty$ norm within a specified tolerance limit. This process is also regarded as part of the trial-and-error design as it affects the frequency shaping of controllers.

3.2 Novel Challenge in Epsilon's Control Design

One of the purposes of the Epsilon rocket, Japan’s next generation solid rocket launcher, is to provide better user friendly interface than any other solid rockets of the world\(^{15-25}\). This involves milder mechanical environment for spacecraft. To achieve this, a special vibration attenuator, the payload attach fitting (PAF), is newly developed to be installed at the satellite attachment to suppress the high frequency vibration (around 50 Hz) caused by the first stage combustion vibration. The mechanism is aimed at reducing its axial rigidity to isolate the vibration and in turn it results in a lower bending frequency of the entire vehicle. This makes the control design absolutely difficult as the rigid body dynamics (0.5 Hz) and the first order bending oscillation (4Hz) become much closer (6Hz for M-V).

To achieve better control characteristics in a straightforward manner, a 2-step approach is adopted in this study. First, the robust control design process, as introduced in the previous section, is applied to the vehicle dynamics without the PAF, which yield the core controller that will roughly provide overall robust stability. Then, a special linear compensator is superimposed in order to improve the stability margins that are inevitably deteriorated by insertion of the PAF dynamics and it is taken to be the form as:

$$F(s) = \left(\frac{\omega_0}{\omega_h}\right)^2 \frac{T_s + 1}{T_s + 1} s^2 + 2\zeta\omega_s s + \omega_h^2$$  (8)

At this stage of the development, virtually the same logic as the M-V rocket’s $\mu$-control (6 degrees of freedom) is taken to be the core control algorithm of the Epsilon, thus the entire controller having 9th order dynamics. The stability check is conducted for the Epsilon’s second stage flight at time mark of burn out when the level of instability caused by the PAF rigidity reaches its maximum. The analysis indicates that the nominal stability can be considered well within the scope of expectation as the gain and the phase margins meet their requirements: 6 dB and 30 degrees, respectively (Fig. 8). It is also revealed that the system achieves enough robust stability: the worst case remains stable as appreciated in

![Figure 8. Bode diagram of the second stage closed system at burn out: the nominal case.](image1)

![Figure 9. Bode diagram of the second stage closed system at burn out: the worst case.](image2)
Fig. 9, which shows the bode diagram under the worst combination of the system parameters. Note that the stability survey is performed by changing the bending rigidities of the entire vehicle with the PAF, the frequency characters of the mobile nozzle, and the modal slope at the sensor location.

4. Conclusion

One of the purposes of the Epsilon rocket, Japan’s next generation solid rocket launcher, is to provide better user friendly interface than any other solid rockets of the world. This involves milder mechanical environment for spacecraft. To achieve this, a special vibration attenuator (PAF) is newly developed to be installed at the satellite-attachment to suppress the high frequency vibration caused by the first stage combustion vibration. The mechanism is aimed at reducing axial rigidity to isolate the vibration and in turn it results in a lower bending frequency of the entire vehicle. This makes the control design absolutely difficult as the rigid body dynamics and the first order bending oscillation become much closer. The proposed design consists of combination of a core controller, a $\mu$-synthesis algorithm to provide robust stability, and a superimposed linear control element to tackle with the effects of the vibration attenuator. It indicates that the obtained control characteristics can be considered well within the scope of expectation. The paper has described the design of the robust attitude control of the Epsilon rocket launcher that will have its maiden launch in summer of 2013.

References


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Nomenclature

\[ a \] : scalar gain of \( W \)
\[ Ac \] : system matrix of the controller \( \in \mathbb{R}^{nc \times nc} \)
\[ Ar \] : system matrix of the reduced plant \( \in \mathbb{R}^{nr \times nr} \)
\[ Bc \] : input matrix of the controller \( \in \mathbb{R}^{nc \times p} \)
\[ Br \] : input matrix of the reduced plant \( \in \mathbb{R}^{nr \times m} \)
\[ Cc \] : output matrix of the controller \( \in \mathbb{R}^{m \times nc} \)
\[ Cr \] : output matrix of the reduced plant \( \in \mathbb{R}^{m \times nr} \)
\[ d \] : disturbance vector \( \in \mathbb{R}^m \)
\[ De \] : feedback gain of the controller \( \in \mathbb{R}^{m \times p} \)
\[ Dc \] : \( \mu \)-feedback gain matrix \( \in \mathbb{R}^{m \times p} \)
\[ Dcp \] : local output feedback gain \( \in \mathbb{R}^{m \times p} \)
\[ G1 \] : scalar gain of \( W1 \)
\[ m \] : order of the plant input (\( =1 \))
\[ nc \] : order of the controller (\( =6 \))
\[ nr \] : order of the reduced plant dynamics (\( =19 \))
\[ p \] : order of the plant output (\( =2 \))
\[ r \] : reference vector
\[ R \] : field of real numbers
\[ s \] : complex variable
\[ T1, T2 \] : parameters of phase lag element
\[ T4, T5 \] : parameters of linear compensator
\[ u \] : control output \( \in \mathbb{R}^m \)
\[ u^* \] : local control output \( \in \mathbb{R}^m \)
\[ w \] : perturbation vector \( \mathbb{R}^p \)
\[ W1 \] : weight on the plant uncertainty
\[ W3 \] : weight on the performance
\[ x_r \] : state vector of the reduced plant \( \in \mathbb{R}^{nr} \)
\[ y \] : plant output \( \in \mathbb{R}^p \)
\[ z \] : state vector of the controller \( \in \mathbb{R}^{nc} \)
\[ y \] : new output vector of the controller \( \in \mathbb{R}^m \)
\[ \alpha , \beta \] : parameters of phase lead element
\[ \omega_1 \] : cut-off frequency of \( W1 \)
\[ \omega_3 \] : cut-off frequency of \( W3 \)
\[ \omega_4, \omega_5 \] : cut-off frequencies of linear compensator
\[ \xi_4, \xi_5 \] : damping factors of linear compensator