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A coupled dynamic loads analysis of satellites with an enhanced Craig–Bampton approach

Jae Hyuk Lim [a], Do-Soon Hwang [b], Kyoung-Won Kim [b], Geun Ho Lee [c], Jin-Gyun Kim [c,d,*]

[a] Division of Mechanical Engineering, Chonbuk National University, 567 Baekje-daero, Deokjin-gu, Jeonju-si, Jeollabuk-do 54896, Republic of Korea
[b] Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon 34133, Republic of Korea
[c] Department of Smart Machine Technology, Korea Institute of Machinery and Materials, 156, Gajeongbuk-Ro, Yuseong-gu, Daejeon 34103, Republic of Korea
[d] Department of Structural Engineering, Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands

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ABSTRACT

In this work, we conducted a coupled dynamic loads analysis (CDLA) of satellites with an enhanced Craig–Bampton (ECB) approach to predict maximum response (acceleration, displacement, and stress). The satellite was subjected to a relatively high frequency launch vehicle (LV) interface load (20–50 Hz) when it was launched by multiple satellite launcher or experienced the combustion instability caused by LV instead of a typical low frequency LV interface load (0–10 Hz). To minimize the error caused by mode truncation, ECB-like formulation, which considers the effect of residual modes, is employed and computes the maximum response of the given dynamic system. By using this method, we found that the response by the ECB model is more accurate and efficient over the classical Craig–Bampton (CB) model due to the enhanced transformation matrix from being subjected to an unexpected high frequency LV load. To demonstrate this performance, we solved several benchmark problems associated with CDLA.

1. Introduction

To investigate the structural safety of spacecraft (SC) while experiencing extreme dynamic loads from critical launch events such as lift-off, wind-gust, and stage separation, couple-dynamic load analysis (CDLA), also termed coupled loads analysis (CLA), has been routinely used in many space agencies and industries [1,2]. To tackle this problem, component mode synthesis (CMS) has been widely used in structural vibration society [3–7]. Recently, Sabatini et al. introduce the advantage of the multibody dynamics simulation for CDLA [8] and, in particular, experimental dynamic substructuring that is to combine analytical and experimental models based on the CMS methods have been mainly issued [9–12].

In conventional CDLA, SC finite element (FE) models composed of many degrees of freedom are reduced to the SC interface nodes and several output nodes by using the Craig–Bampton (CB) method [3] that is the most well known CMS method. Then, these models are delivered to the launch vehicle (LV) company and the LV FE model is assembled them for the transient simulation at several critical launch events to find out the maximum response.

In the case of small LVs, especially for low earth-orbit (LEO) launches less than 1000 km, the coupling effect between SC and LV is negligible because the minimum lateral natural frequency of SC needs to be sufficiently higher than the LV's natural frequency (<10 Hz). However, in the case of large LVs, which have the capability to shoot heavy payloads farther than LEO, they usually employ solid boosters which subject spacecraft to a frequency acceleration higher than 20 Hz due to the combustion characteristics. Furthermore, they provide a launch-service for satellites to LEO in the form of dual or multiple launches, but this kind of launch service generates another high frequency vibration source due to the structural interaction between the payload satellites that was quite unexpected and has never described in launch-vehicle manual. There was an unexpected vibration input source of around 28 Hz [13], as shown in Fig. 1. In addition, pogo oscillation (see Fig. 2), a thrust axis vibration in the range of 5 to 50 Hz depending on the propulsion system caused by the combustion instability of rocket LV with the liquid engine, is also applied to the spacecraft [14,15].

In order to accurately predict the maximum response of SC at the launch events under such circumstances, a more sophisticated reduced model is needed because the conventional CB model has some errors as the exciting frequency of input source becomes higher. The main source of the error is due to ignoring the contribution of a high frequency structural response. In other words,

* Corresponding author at: Department of Smart Machine Technology, Korea Institute of Machinery and Materials, 156, Gajeongbuk-Ro, Yuseong-gu, Daejeon 34103, Republic of Korea.
E-mail addresses: jingyun.kim@gmail.com, jingyun@kimm.re.kr (J.G. Kim).

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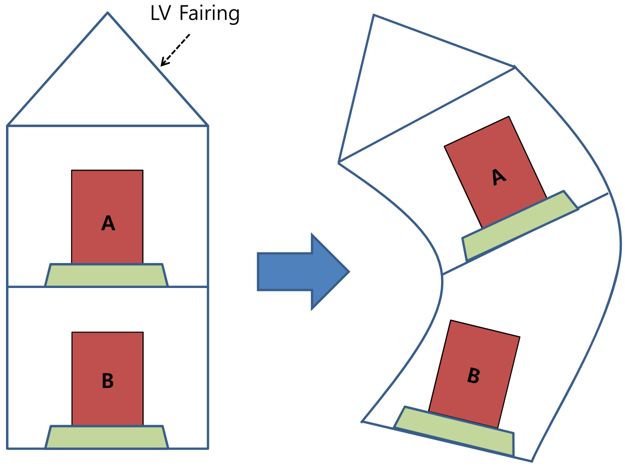

Fig. 1. High structural mode due to multiple SC launches.

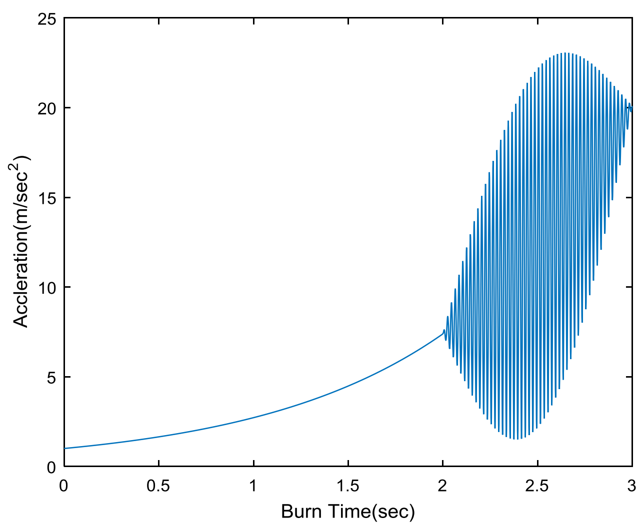

Fig. 2. High frequency SC acceleration by combustion instability (pogo oscillation).

when we construct a CB model for CDLA, we carefully have to compute the eigenfrequency over the frequency range of interest with a proper mode selection technique. Such truncation errors in the CB model happen when the other modes located outside of the frequency domain of interest may also have significant contributions. Namely, these modes have high modal participation factors or these modes are locally very relevant, as in the case of flexural appendages.

In order to compensate for such an effect, there have been several approaches utilized [16–18]. Among those, the MA (modal acceleration) method has been frequently employed to compensate for modal truncation errors. In this method, the quasi-static contribution of the non-retained modes whose eigenfrequency is located outside the excitation frequencies is computed. To improve the accuracy of MA further, the MTA (modal truncation augmentation) method has also been proposed. This method tries to compensate the error caused by the truncation of residual modes. Thus, it was chosen for many commercial software such as NASTRAN [19] by adding extra orthogonal mode shape vector, termed the residual vector. By compensating for this term, the error arising from the mode truncation is efficiently diminished. However, it is known that such artificial mode augmentation slightly violates the equation of the motion of dynamics systems [16,18]. In other words, it can increase the accuracy of frequency response functions and transient responses, but is theoretically less rigorous, even generating 'mass-less mode' [19].

Recently, a more simple and accurate approach called ECB (enhanced CB) method was proposed by Kim and Lee [20]. In this method, high-frequency modal effects can be considered by the residual flexibility within the transformation matrix [21,22]. Note that this method does not use any artificial terms, like MTA, thus making the method more complete in a theoretical sense. Therefore, users do not need to set up the parameters, such as the number of basis, like the conventional MTA method. Furthermore, its procedure is almost equivalent to CB, except for the additional term of high frequency contributions in the transformation matrix only. Thus, it turns out that ECB offers a more precise reduced-order modeling in contrast to CB [23].

The goal of this work is to provide an accurate approach for CDLA with ECB-like formulation. The outline of the paper is as follows. In Section 2, we explain how to construct an ECB model in contrast to CB. This is followed by the formulation of CDLA along with the output transformation matrix (OTM). Next, in Section 3, to demonstrate the efficiency and accuracy of the proposed scheme, we solve a benchmark problem of a rectangular plate with two fixed edges to investigate its characteristics in detail by comparing the performance with the CB model. In Section 4, we demonstrate the robustness of the proposed scheme by conducting the CLA of the satellite with high frequency LV interface loads. Finally, we conclude the paper with closing remarks in Section 5.

2. Enhanced Craig–Bampton method and coupled dynamics loads analysis

2.1. Classical and enhanced CB formulations

We here introduce the classical and enhanced CB formulations [3,20]. The equations of the motion of linear dynamic systems neglecting the damping effect can be written as

$$\mathbf{M}_g\ddot{\mathbf{u}}_g + \mathbf{K}_g\mathbf{u}_g = \mathbf{f}_g, \tag{1}$$

$$\mathbf{M}_g = \begin{bmatrix} \mathbf{M}_b & \mathbf{M}_c \\ \mathbf{M}_c^T & \mathbf{M}_L \end{bmatrix}, \qquad \mathbf{K}_g = \begin{bmatrix} \mathbf{K}_b & \mathbf{K}_c \\ \mathbf{K}_c^T & \mathbf{K}_L \end{bmatrix},$$
$$\mathbf{u}_g = \begin{Bmatrix} \mathbf{u}_b \\ \mathbf{u}_L \end{Bmatrix}, \qquad \mathbf{f}_g = \begin{Bmatrix} \mathbf{f}_b \\ \mathbf{f}_L \end{Bmatrix}, \tag{2}$$

where $\mathbf{M}$ and $\mathbf{K}$ are the mass and stiffness matrices, and $\mathbf{u}$ and $\mathbf{f}$ are the displacement and force vectors, respectively. The subscript g indicates the global structure. The other subscripts L, b, and c indicate internal, boundary interface and coupling matrices, respectively. Its eigensolution can be computed from

$$\mathbf{K}_g\boldsymbol{\psi}_i = \boldsymbol{\gamma}_i\mathbf{M}_g\boldsymbol{\psi}_i, \quad i = 1, 2, \ldots, N_g, \tag{3}$$

where $\boldsymbol{\gamma}_i$ and $\boldsymbol{\psi}_i$ are the i-th eigenvalue and eigenvector of the global structure, respectively, and N_g is the number of DOFs in the global structure. Note that $\boldsymbol{\gamma}_i$ and $\boldsymbol{\psi}_i$ are the square of the i-th natural frequency (ω_i^2) and the corresponding mode in the structural dynamics, respectively.

In the classical CB approach [3], the global displacement vector $\mathbf{u}_g$ can be defined as

$$\mathbf{u}_g = \begin{Bmatrix} \mathbf{u}_b \\ \mathbf{u}_L \end{Bmatrix} = \mathbf{T}\begin{Bmatrix} \mathbf{u}_b \\ \mathbf{q} \end{Bmatrix}, \qquad \mathbf{T} = \begin{bmatrix} \mathbf{I}_b & \mathbf{0} \\ \boldsymbol{\Phi}_R & \boldsymbol{\Phi}_L \end{bmatrix},$$
$$\boldsymbol{\Phi}_R = \mathbf{K}_L^{-1}\mathbf{K}_C^T, \qquad \boldsymbol{\Phi}_L = \begin{bmatrix} \boldsymbol{\Phi}_d & \boldsymbol{\Phi}_r \end{bmatrix}, \qquad \mathbf{q} = \begin{Bmatrix} \mathbf{q}_d \\ \mathbf{q}_r \end{Bmatrix}, \tag{4}$$

in which $\mathbf{q}$ is the generalized coordinate of the internal degrees of freedom (DOFs), and $\mathbf{I}_b$ is the identity matrix of the interface boundary DOFs. $\boldsymbol{\Phi}_R$ and $\boldsymbol{\Phi}_L$ are the matrices of the interface constraints and fixed interface normal modes, respectively. Then, $\boldsymbol{\Phi}_L$