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MACHINERY VIBRATION ANALYSIS AND CONDITION MONITORING: A COLLABORATIVE APPROACH

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Abstract

Launch of a space vehicle puts enormous demands on supporting equipment and ground systems that must be safe and reliable so as to guarantee mission success. One such ground system is the NASA's crawler transporter, a 3 million kilogram behemoth, built in the 1960's, which moves the 6 million kilogram Space Shuttle to the pad 6-8 kilometers away. This paper discusses vibration analysis and condition monitoring efforts of crawler transporter system components. Modal test and finite element analysis were performed on the crawler transporter systems to assess their vibratory effect on the Space Shuttle Vehicle (SSV). Lastly, focus is on a new software tool to aid engineers and managers who must communicate, collaborate, and visualize modal vibration and structural analysis results, so as to make safe and cost-effective decisions.

INTRODUCTION

The SSV sees relatively high vibration loads during launch, ascent, descent and landing phases of the mission. However, of interest in this paper is the rollout phase. Assembled and mounted on the Mobile Launch Platform (MLP), the SSV is lifted and transported to the launch pad by the Crawler Transporter (CT) and the typifies the rollout phase as depicted in Figure 1. Each rollout presents a unique speed trace with variations in steady-state and transient conditions that potentially could lead to damaging vibratory environment for the launch vehicle. Vibration levels during rollout are of low amplitude and frequency, however, the duration of the rollout phase is typically high, up to 6-8 hours. Thus, the elements of the SSV have required periodic fatigue analyses as a part of the mission life certification [1].

ANALYSES METHODOLOGY

The overall effort summarized in this paper included instrumented field tests on variety of SSV components, finite element stress and vibration analyses, test-analyses corroboration involving multiple NASA centers, and supported by scores of contractor engineers and analysts. The elements and framework of the analyses is outlined next:

- Vibration Analysis
- Structural Dynamics
- Condition Monitoring
- Collaborative Approach

VIBRATION ANALYSES

Instrumented Rollout Tests: Actual instrumented rollout tests with various configurations full SSV and partial SSV were conducted to assess SSV system vibrations. To identify vibrations unique to CT speeds, tests were run from .5 to .9 mph, with .9 mph being the typical maximum CT operational speed. Some evidence was found that unique speed related vibration of the CT were attributable to the launch vehicle vibration during rollout to the pad.

Finite Element Analysis: Figure 2, shows the typical structural subsystems modeled using finite element analysis (FEA) code MSC/NASTRAN. These combined models of CT, MLP, and solid rocket boosters (SRB), were used to determine overall effect of CT system characteristics on the response of the CT/MLP/SRB and the entire SSV system. Agreement between the predicted mode and frequencies from actual rollout tests and those from FEA analysis was found to be very good as outlined in Table 4[1].

Rotating Equipment Analysis: As a part of identifying vibration sources within the analysis was performed on CT rotating equipment to determine components that would are the source of forcing functions to affect SSV. Based on this review, shoe pass and tread belt mechanism frequencies and their 2 and 3 multiples were found to be suspect at critical CT operating speeds. CT shoe pass and spacing frequencies were also found to influence the entire SSV vibration during rollout as depicted in Table 1[1].

STRUCTURAL DYNAMICS

Static Load Test: Observation of fatigue cracks on CT shoes during this juncture, led to a comprehensive structural evaluation to assess the root cause of impending failure. Earlier observation of shoe passing frequency coupled with shoe and roller spacing frequencies was critical for structural fatigue. In addition, subsurface casting defects compromised the structural integrity of these old Apollo-era shoes. To evaluate integrity, static compression tests were conducted [2].

Dynamic Rollout Test: Additionally, dynamic rollout tests with instrumented (strain-gauged) shoes were conducted to validate the finite element analytical models to predict the shoe load/stresses and compute fatigue life or mileage to failure for the old shoes. Static load-strain calibration was later used to compute dynamic loads and stresses for partial and full stack SSV during rollout [2].

Finite Element Analysis: A NASTRAN full shoe finite element model (Figure 3), was crucial in conducting sensitivity analysis as well as identifying high stress zones. It also was crucial in predicting remaining useful life of existing shoes and mileage to failure for the new shoes. Table 3 [2], summarizes fatigue life projections for variety of conditions, with average useful life of 1983 miles closely agrees to the current CT mileage of 1700+ miles. Over 1000 new shoes were then fabricated to refurbish the two Crawlers, to alleviate and eliminate any and all impact on future SSV launch pad rollouts.

CONDITION MONITORING

Modal Analysis: To ensure the structural integrity of newly installed, a comprehensive assessment of available NDT techniques was undertaken. Experimental modal analysis was deemed as a potential screening tool for condition monitoring of CT shoes. Damage is related to changes in physical properties (mass, damping, and stiffness), which in-turn are linked to changes in modal parameters (frequencies, damping ratios, and modes shapes). The modal vibration method adopted was to detect frequency shifts of damage, flaws, or discontinuities due to the resulting stiffness changes.

Finite Element Analysis: NASTRAN and ANSYS models of full shoe were developed to provide test-analysis corroboration of natural frequencies, with and without existence of cracks, discontinuities, or damage. Experimental modal analysis has not been applied to such a large casting (over 1 ton) and in-situ on the CT where the boundary conditions, shoe weight variability, flaw characteristics, impact amplitude and location, and measurement setup, can all affect end results. Frequency shifts were found more pronounced for axial mode rather than bending modes. Figure 5, depicts one of the primary frequency mode shapes.

COLLABORATIVE APPROACH

The CT test and modal effort was carried out over a period of several years and required constant interfacing between various entities (Figure 4). It comprised of multiple FE analysts and test personnel (located within various NASA centers and at remote locations), working on variety of analyses platforms that generated enormous results database. This modal database produced by each analyst or group of analysts was summarized ultimately into a CAE report with a few images is typically sent to NASA management for design review. Although, managers are responsible for design decisions, they neither have the tools, nor the expertise to query stress and modal analysis results expeditiously. The native FEA tools (NASTRAN, ANSYS, etc.) are designed for analysts more than the managers.

Here is the major dilemma or bottleneck in the design review process. It is imperative that modal, stress, and dynamic results must be visualized to make engineering judgment [4]. It also has been identified that the static images or AVI files do not contain enough information for reviewing modal analysis results. At the same time managers cannot use CAE post processors due to complexity and lack of collaborative features.

A new type of visualization software (VCollab) is being evaluated by United Space Alliance at the Kennedy Space Center for CT modal results management (Figure 5). VCollab captures many analysis results into a highly compressible 3D visual (VCZ) file and provides a consistent platform to visualize 3D CAE results from many FEA and CFD software. Modal analysis results from different CAD and CAE software can be captured in 3D and then embedded into PowerPoint or Word document or WEB pages and reused and shared easily with management, designers, analysts and test engineers. This enables non-analysts to easily access, view, manipulate and review the 3D CAE results out of MS office applications or IE browser without knowing or having the native applications. If JPEG files are first level of communication media format, AVI as the next level, then VCZ can be considered as the third level of media format for light weight communication of CAE results, where users can not only visualize and play animations but also manipulate the model and results to increase effectiveness of management decision-making process. In a nutshell, what PDF files are to Word files and CAD files, VCollab is to the CAE industry. Figure 5 and 6, depicts an examples of such communication, visualization and collaboration.

CONCLUDING REMARKS

A comprehensive assessment of CT components and systems was performed, so as to understand their effect on the fatigue impact of major SSV elements as a part of the mission life certification. Shoe pass, shoe and roller spacing, and tread belt mechanism were the main forcing frequencies of CT at nominal speed. It was surmised that it could lead to highest vibration conditions during the SSV rollout to the pad. To ensure the structural integrity of the newly procured shoes, a modal method for condition monitoring technique is presented. Lastly, an overview and advantages of using a communication, visualization and collaboration solution to share, view, collaborate and manage large amount of modal data, to help and impact the decision making process, is outlined.

REFERENCES

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2. K.Meyer, R.Burton, A. Gosselin, and R.Margasahayam, "Space Shuttle Crawler Transporter Truck Shoe Qualification Tests and Analyses for Return-to-Flight", *Proceedings of the Twelfth International Congress on Sound and Vibration (*ICSV 12), 11-14 July 2005, Lisbon, Portugal.
3. H.V. Panossian, "Characteristic Differences Between the Modal Parameters of Cats and Forged Structures", *Journal of Aircraft*, Vol. 29, No. 3, Engineering Notes.
4. K. Gruber, "CAE Data Management at Audi AG", *MSC Software EMEA VPD Conference*, November 2005.

Figure 1. CT, MLP, and SSV Rollout to Launch Pad [Courtesy NASA Public Affairs]

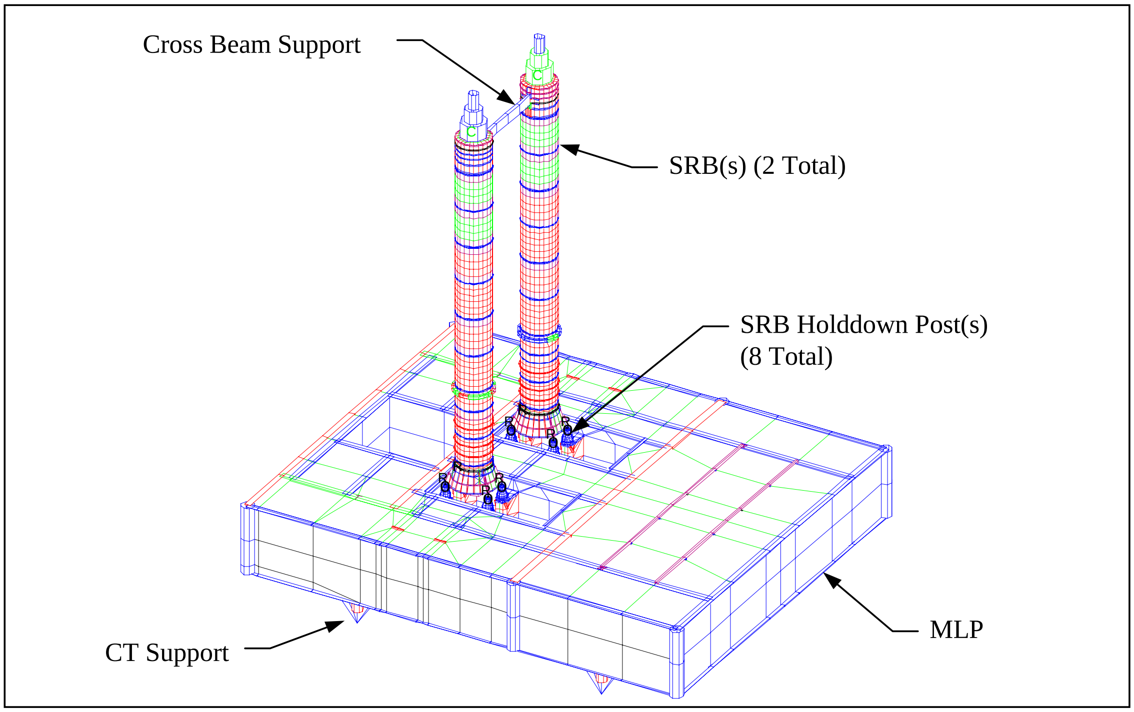
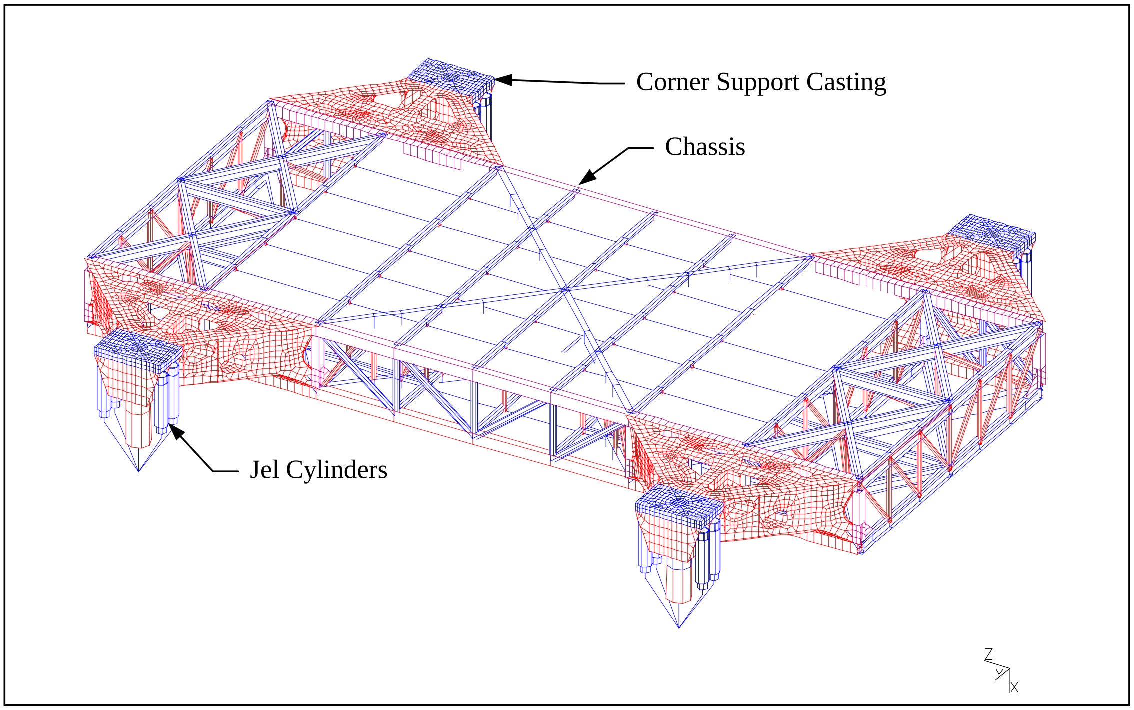


Figure 2. SRB, MLP, and CT Structural Math Model [Reference 1]



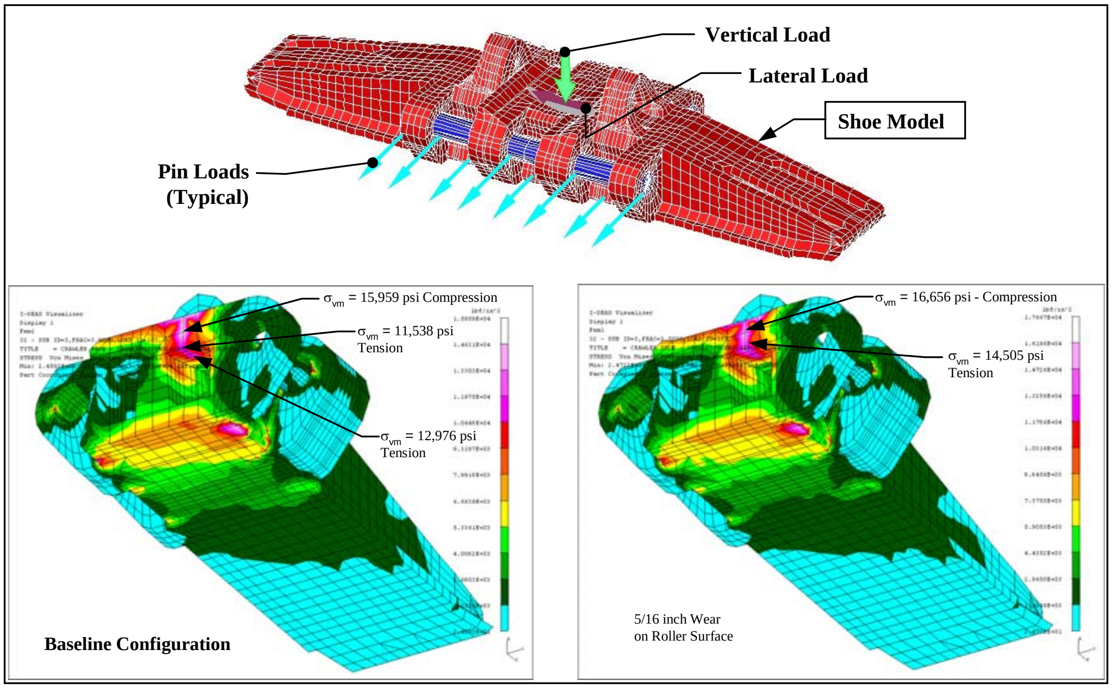


Figure 3. Typical Shoe FE Model used for Stress and Vibration Analysis [Reference 2]

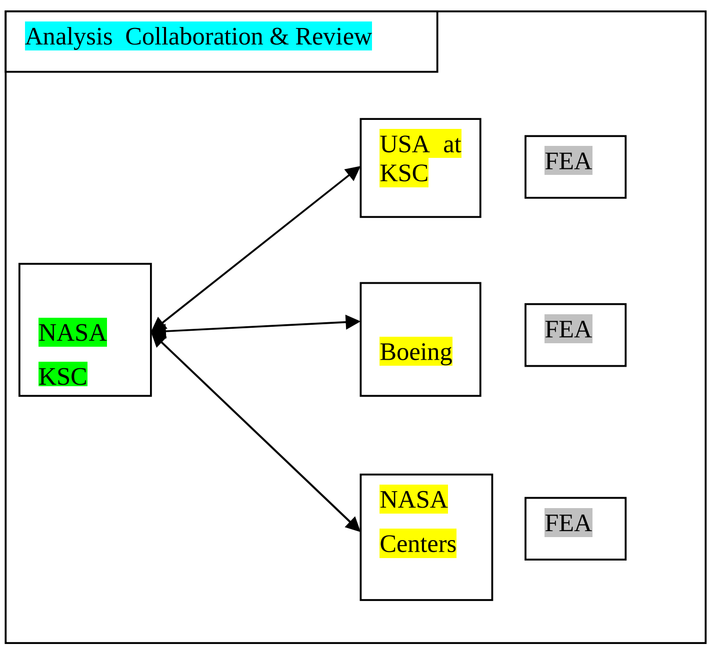


Figure 4. A Collaborative Approach for Analysis, Design review, and Decision-making

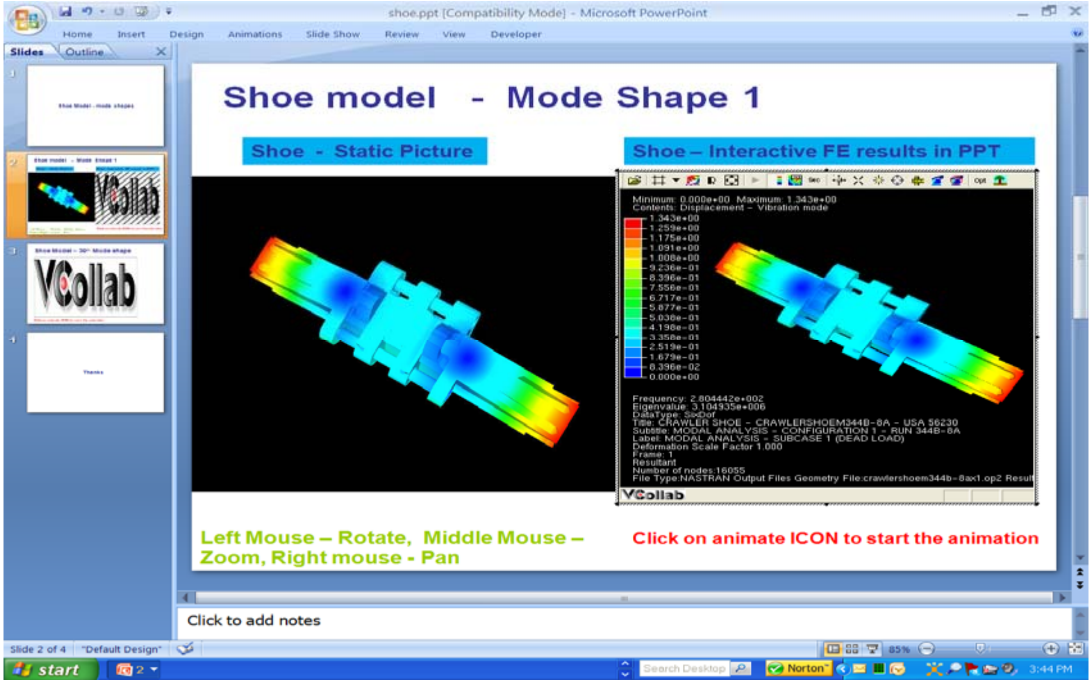


Figure 5. Visualization and Communication Tool for Engineers and Managers

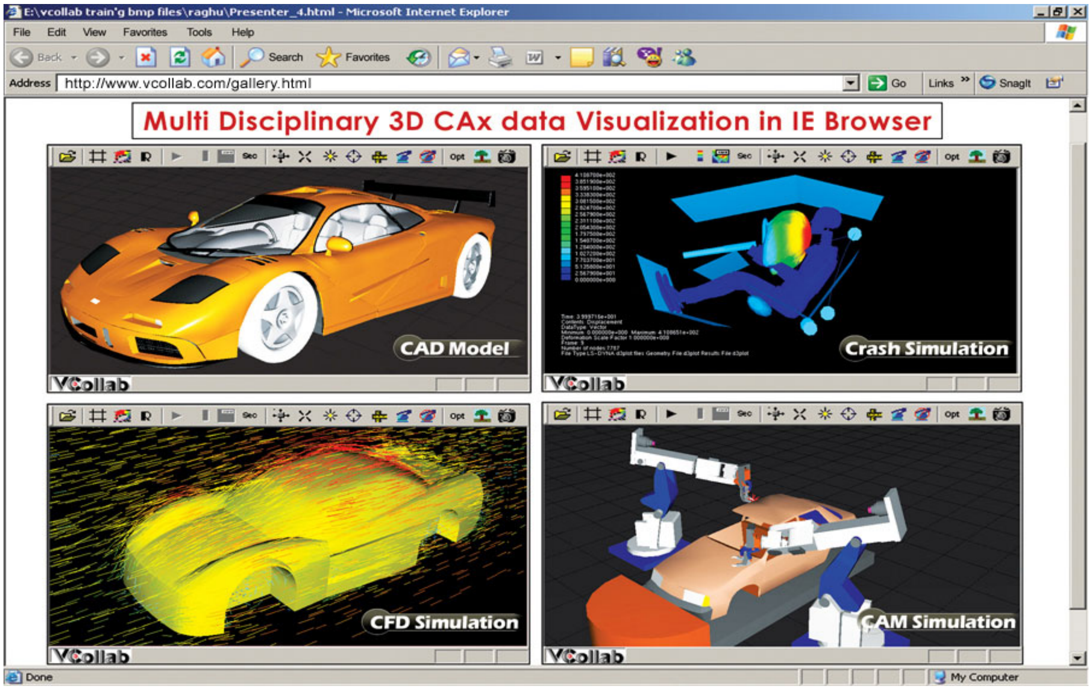


Figure 6. Data Visualization in IE Browser (Word, PowerPoint, and Excel options)