DAMAGE DETECTION IN THE COMPOSITE FUEL TANK BY VIBRATION MEASUREMENT APPROACH

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ABSTRACT:
Demand of composite fuel tank for the space vehicles keeps increasing globally in aerospace industry, and requires of a mean to predict its service life. Reported are an experimental investigation on the modal properties and dynamic response of composite fuel tank filled with fluid under external excitation in the transverse direction, and a vibration signal which was obtained when the composite fuel tank filled with water was under impulsion until it was failure. Proposed in this study is a method to detect the damage of the composite fuel tank with the scarce gradual damaged vibration signal. The experiment setup is also described in detail with inclusion of modeling a damaged situation of a structure. The damage detection algorithm is developed applying a residually generated form of a subspace-based covariance-driven identification method and the vibration signal analysis. Results of the modal identification and the damage detection are reported in this paper.

KEYWORDS:
Composite fuel tank, Experiment, Vibration based, Damage detection

1. INTRODUCTION

For a next generation rocket, a fuel tank made from carbon fiber reinforced plastics is one of the key technologies. Composite tanks often suffer damages under its extreme working environment. As important and valid tools, in the past years, lots of non-destructive evaluation (NDE) techniques including ultrasonic scanning, acoustic emission (AE) [1-3], radiography, stimulated infrared thermograph (SIT), etc. have been developed, and they are carried out according to a regular time schedule [4-6]. The structure has to be taken out of service during each inspection, causing serious financial implications for the user. That is why much research effort is now focused on real-time monitoring techniques. In this way one can collect up-to-date information concerning a broad range of structural and/or environmental parameters. By evaluating these parameters one can identify potential problems at an early stage and take cost effective remedial actions. On recent years, optical grating fibre attracts more and more attention due to its excellent sensing and mechanical performances and ability of monitoring online [7-10]. But it still can only measure the local deformation, but not the damage, such as the impacted one, that far away from the location of optical fibre sensors. This characteristic of optical fibre limits its applications. Today, either online monitoring techniques or automatic global vibration-based monitoring methods are proved to be useful for the detection and localization of structural damages which might be occurred far from the location of sensors [11-13]. Vibration-based methods require of understanding the dynamic characteristics of structures well in order to identify damages in variance with the dynamic property changes. Some vibration-based methods had been developed [11-14], but most of them required a set of exact experimental modes, which is difficult to obtain due to the noise, therefore statistical model-based algorithms are more feasible [15, 16]. For the fluid filled structures, fluid-structure interaction makes their dynamic responses more complex.
The objective of this study is to assess a structural damage situation, of which structure is composed of a filament wound composite fuel tank filled with fluid, by using the proposed damage detection method with comparison of the experimental vibration data. The paper first describes the model details of CFRP tank and

experimental setup. Then it is followed by a description of test procedure and damage situation. In Section 3, described are statistical interpretations for determining the parameters of dynamic systems and a stochastic subspace-based covariance-driven modal identification method in order that the proposed detection algorithm is justified. The implementation of the damage detection, results and analysis are presented in Section 4. Section 5 concludes our investigations and recommends further studies.

2. COMPOSITE FUEL TANK AND EXPERIMENTAL SETUP

2.1. Composite Fuel Tank

The composite fuel tank used in this work is a 251mm-long cylinder with an isotension dome at each end. Whole tank is manufactured by filament winding carbon fibres (T1000) around aluminium liners. The winding angles for both upper and lower dome are variety from 9.1^{o} to 65.6 ^{o} and from 17.2^{o} to 74.1^{o}. The fibre layers of the tank are 6 layers oriented in various directions in the helical direction plus 9 layers around a diameter. The layer construction of the cylindrical part from exterior to interior is [$\pm$13^{o}/0^{o}]. Each layer thickness of CFRP is 0.2 mm, and aluminium liner thickness is 1mm. The middle cylinder is 745 mm in diameter. Figure 1 shows the detailed size of the tank. Epoxy resin is used as the matrix.

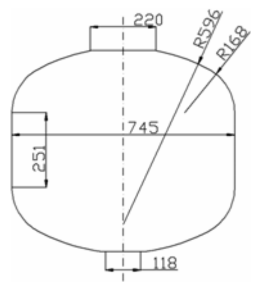

Figure 1 Schematic drawing of the composite fuel tank

2.2 Experimental Setup

A test was designed for investigating the dynamic responses of the composite fuel tank filled with liquid. In this test, total 24 accelerometers, manufactured by PCB, were used to record the dynamic response of the structure. The response frequency of sensors was 2-8000Hz. All sensors positions were designed according to the modal analysis results of the finite element method. Six sensors in one group were arranged in one line, and four groups of sensors were placed symmetrically. All sensors were mounted on the surface of the CFRP tank as shown in Figure 2.
For simulating the ambient vibration in real work condition, the tank was placed on and excited by shake table. The shake table used in this work, which was installed in Harbin Institute of Technology, was type of UD-T2000 made by Unholtz-Dickie Company, USA. For simulating the boundary condition in real work condition, and also mount the tank on the shake table, during the whole test, the composite fuel tank was fixed in a steel base, which was designed specially to ensure that its natural frequencies keep away from ones of the tank tested. Acceleration signal was collected by the data acquisition system SD-2570, made by Spectral Dynamics Company, USA.

2.3 Test Method

Sources of vibration and noise for the composite fuel tank involve the noise of engine and the other non-periodic vibration source. All above vibration excitations can be characterized with broadband stationary noise. During the procedure of test, the sampling rate is 5120Hz, which is determined according to results of the finite element analysis, to ensure capturing all concerned modes.

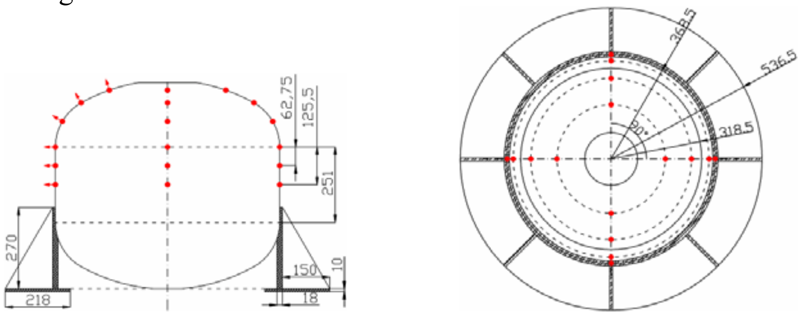

Figure 2 Configuration of the accelerometers

2.4 Experimental Results and Discussion

The duration of test was about 15 seconds until the composite fuel tank was found damaged obviously. The damaged area located near the steel support and around mostly the whole cylinder. Shear fractured fibres and delaminated CFRP can be observed, shown in Figure 3. Obviously, the stiffness of the damaged area reduces, which results in the change of the modal parameters of the structure, such as the decrease of frequencies.
For exploring the change of the modal parameters due to the structural damage, the stochastic subspace modal identification (SSI) algorithm was performed to obtain the modal parameters, i.e. frequencies, damping coefficients and mode shapes. Figure 4 shows the stabilization diagram of SSI. All identified parameters are listed in Table 3.1. From this table, it's hard to distinguish the difference of the frequencies between the undamaged and damaged structures. Therefore, it's necessary to identify the damage with more exact and strict algorithm.

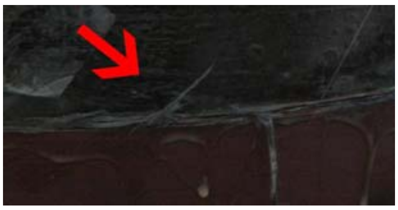

Figure 3 The damaged area in the composite fuel tank

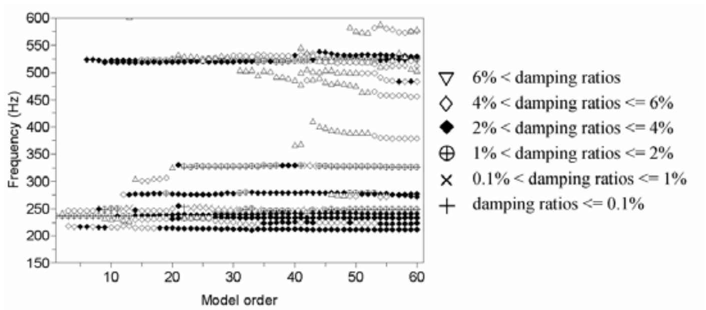

Figure 4 The typical identification results with SSI algorithm shown as stabilization diagram

3. DAMAGE DETECTION ALGORITHM

In this section, a damage detection algorithm is presented. For the candidate structure, we assume that its

Table 3.1 Identification results with SSI algorithm

Mode		1	2	3	4
Frequencies (Hz)	Data set 1	211.4139	232.7329	279.5195	520.1611
	Data set 2	210.8042	235.1615	277.3879	513.4572
	Data set 3	212.5469	230.3622	282.9640	511.3897
	Data set 4	213.1973	234.0152	280.5574	519.4102
	Data set 5	211.6180	231.7568	280.5301	521.6179
Damping ratios (%)	Data set 1	2.5502	2.5858	2.1988	2.6876
	Data set 2	2.9435	2.1274	1.5903	1.2505
	Data set 3	2.9084	2.9242	2.1107	1.8619
	Data set 4	1.8204	3.6582	2.2786	2.9384
	Data set 5	2.6310	4.0551	2.6263	1.5051

mechanical behaviour can be described by a linear dynamical system, and that, in the frequency range of interest, the input forces can be modeled as a non-stationary white noise. This results in:

$$M\ddot{Z} + C\dot{Z} + KZ = v,\ Y = LZ \tag{3.1}$$

where M, C, K are the mass, damping and stiffness matrices respectively, (high dimensional) vector Z collects the displacements of the degrees of freedom of the structure; the external (non measured) force v is modeled as a non-stationary white noise with time-varying covariance matrix $Q_v(t)$, measurements are collected in vector Y, and matrix L indicates which components of the state vector are actually measured (where the sensors are located). The modes or eigen-frequencies denoted generically by μ, the eigen-vectors ϕ_μ, and the mode shapes denoted generically by ψ_μ, are solutions of:

$$\det(\mu^2 M + \mu C + K) = 0,\ (\mu^2 M + \mu C + K)\phi_\mu = 0,\ \psi_\mu = L\phi_\mu \tag{3.2}$$

Sampling model (3.1) at rate $1/\tau$ yields the discrete time model in state space form:

$$\begin{cases} X_{k+1} = FX_k + V_{k+1} \\ Y_k = HX_k \end{cases} \tag{3.3}$$

where the state and the output are:

$$X_k = \begin{pmatrix} Z(k\tau) \\ \dot{Z}(k\tau) \end{pmatrix},\ Y_k = Y(k\tau) \tag{3.4}$$

And, V_{k+1} is the unmeasured state noise, which is assumed to be Gaussian, zero-mean, white.
The modal parameters defined in (3.2) are equivalently found from the eigen-structure $(\lambda,\ \varphi_\lambda)$ of the state transition matrix F:

$$e^{\tau\mu} = \lambda,\ \psi_\mu = \phi_\lambda = H\varphi_\lambda \tag{3.5}$$

eigenvectors are real if proportional damping is assumed, that is $C = \alpha M + \beta K$. The λ's and ϕ's are pair wise complex conjugate. The collection of modes ($\lambda,\ \phi_\lambda$) forms a canonical parameterization of the pole part of the system in (3.3). From now on, the collection of modes is also considered as the system parameter θ:

$$\theta = \begin{pmatrix} \Lambda \\ \text{vec}\Phi \end{pmatrix} \tag{3.6}$$

where Λ is the vector whose elements are the eigen-values λ, Φ is the matrix whose columns are the mode shapes ϕ_λ's, and vec is the column stacking operator.

In the proposed method, the damage detection is stated as the problem of detecting changes in the canonical parameter vector θ, defined in (3.5). It is assumed that a reference value θ_0, which generally is identified using recorded data on the undamaged system, is available. Given, on one hand, a reference value θ_0 of the model parameter and, on the other hand, a new data sample, the detection problem is to decide whether the new data are still well described by this parameter value or not. The design of the proposed damage detection algorithm is based on a general statistical approach, which aims at transforming a large class of detection problems concerning a parameterized stochastic process into the universal problem of monitoring the mean of a Gaussian random vector. This approach basically addresses the early warning of small deviations of the system parameter. The key ideal is to define a convenient residual, which is tightly associated with a relevant parameter estimation method, and to compute the sensitivity of the residual with respect to damages and the uncertainty in the residual due to process noise and estimation errors. Moreover, the residual can be shown to be asymptotically Gaussian.

The system eigen-structure can be estimated through the SVD of an empirical Hankel matrix $\hat{H}_{p+1,\,q}$, possibly pre- and post-multiplied by invertible matrix gains, as described in ref. [16]. This yields, in the left factor, an estimate $\hat{O}$ for the observability matrix O, From $\hat{O}$, estimates $\left(\hat{H},\, \hat{F}\right)$, and $\left(\hat{\lambda},\, \hat{\phi}_\lambda\right)$ are recovered. How to write the estimating function associated with the parameter vector θ in (3.4), and implicitly used in the subspace algorithm, comes from the following remark. Assume that eigenvectors of matrix F are chosen as a basis for the state space of model (3.3). In this basis, the observability matrix is written as [15]:

$$O_{p+1}(\theta) = \begin{pmatrix} \Phi \\ \Phi\Delta \\ \vdots \\ \Phi^{\Delta} p \end{pmatrix} \tag{3.7}$$

where diagonal matrix Δ is defined as $\Delta = \text{diag}(\Lambda)$, and Λ and Φ are as in (3.5). Whether a nominal parameter θ_0 is in agreement with a given output covariance sequence $(R_j)_j$ is characterized by:

$$O_{p+1}(\theta_0) \text{ and } H_{p+1,\,q} \text{ have the same left kernal space.} \tag{3.8}$$

This property can be checked as follows. From the nominal modal parameter vector θ_0, compute $O_{p+1}(\theta_0)$ using (3.6), and perform e.g. a SVD of $O_{p+1}(\theta_0)$ for defining its left kernel space, namely extracting an orthonormal matrix S such that $S^TS=I$s and :

$$S^T O_{p+1}(\theta_0) = 0 \tag{3.9}$$

Matrix S depends implicitly on parameter θ, is not unique − two such matrices are related through a post-multiplication with an orthonormal matrix U, but can be treated as a function of θ_0, denoted by $S(\theta_0)$. The parameter θ_0 which actually corresponds to the output covariance sequence $(R_j)_j$ is characterized by:

$$S^T(\theta_0) H_{p+1,\,q} = 0 \tag{3.10}$$

Assume now that a reference parameter θ_0 and a new data sample $Y_1, \ldots, Y_n$ are available. For checking whether the data agree with θ_0, the idea is to compute the empirical covariance sequence and fill in the empirical block-Hankel matrix $\hat{H}_{p+1,\,q}$ from the new data and to define the residual:

$$\zeta_n(\theta_0) = \sqrt{n}\,\mathrm{vec}(S^T(\theta_0)\hat{H}_{p+1,q}) \tag{3.11}$$

where n is the number of the measured data set. Let θ be the actual value of the parameter for the system which generated the new data sample, and E_θ be the expectation when the actual parameter is θ. It results from (3.10) that:

$$\mathrm{E}_\theta(\zeta_n(\theta_0)) = 0 \quad \text{iff } \theta = \theta_0 \tag{3.12}$$

In other words, vector $\zeta_n(\theta_0)$ in (3.11) has zero mean in the absence of change in θ, and nonzero mean in the presence of a change (damage). Consequently it plays the role of residual.
For the testing if $\theta = \theta_0$ holds true requires the knowledge of the distribution of $\zeta_n(\theta_0)$. But this distribution is generally unknown, so one manner to circumvent this difficulty is to use the statistical local approach. Specifically, a χ^2–test is employed to decide residual ζ_n is significantly different from zero or not, which should be compared to a threshold [17]:

$$\chi_n^2 = \zeta_n^T \hat{\Sigma}^{-1}\hat{J}(\hat{J}^T\hat{\Sigma}^{-1}\hat{J})^{-1}\hat{J}^T\hat{\Sigma}^{-1}\zeta_n \tag{3.13}$$

where J is the consistent estimate of $J(\theta_0)$, that is the sensitivities of the residual with respect to the monitored parameters; $\hat{\Sigma}$ is the consistent estimate of $\Sigma(\theta_0)$, that is the asymptotical residual covariance.

4. IMPLEMENTATION, RESULTS AND ANALYSIS

The proposed subspace-based damage detection method has proven useful in a number of application examples, which are simulated and laboratory mechanical structures. In this paper, we present the results of damage detection for the composite fuel tank. As stated above, after collecting the structural responses, the steps of the proposed damage detection algorithm may be summarized briefly as following: 1) Run the modal identification on the undamaged data with subspace method to obtain the nominal model θ_0; 2) Compute the estimates of the sensitivity $J(\theta_0)$ and residual covariance matrices $\Sigma(\theta_0)$; 3) Apply the χ^2–test on each segment data and determine if the structure is damaged. In the following subsection, the damage detection results are shown.

4.1 Reference Modal Parameters

The purpose of modal identification is to obtain the dynamic properties in the structural safety status as the reference for the further analysis. In this work, this step also accord with obtaining the nominal model θ_0. Thus, the modal parameters recovered from Data 1 listed in Table 3.1 are used as the reference modal parameters.

4.2 Damage Detection and Analysis

After obtained the modal parameters for the undamaged structure, actually we have finished the steps up to Equation (3.5). Then, above identification results will be considered as the reference data for computing the consistent estimates of mean and covariance of the residual $\zeta_n(\theta_0)$: $\hat{J}$ and $\hat{\Sigma}$. Finally, as stated above, the proposed damage detection method was applied to the reference data, namely computing the χ^2-test for the other data set. The result is shown in Figure 5, where the x and y axis represent respectively the index of data set, and the χ^2-test value, i.e. the damage index. As stated above, non-zero χ^2-test indicates structure changes, namely structural damage. For this composite structure, it could be observed that actual structural fracture propagated and augmented rapidly in the last moment of this experiment. It indicated that the structural damage should increase in a short time. From Figure 5, values of χ^2-test just shows the similar phenomenon. Thus the χ^2-test value could yield to some measure of the damage level, but is unable to quantify the damage accurately. The result of the experiment indicates that the proposed method is able to assess the damage in the composite fuel tank.

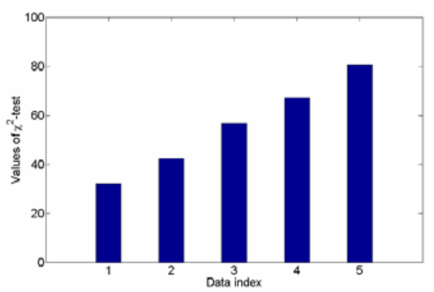

Figure 5. Results of damage detection

5. CONCLUSION

Recent studies and/or R & D are focusing on damage detection and safety evaluation of composite fuel tanks. Currently published techniques have competence to predict or detect the damages and/or safety evaluation, but for current techniques, such as non-destructive evaluation (NDE), it is difficulty to provide on-line and convenient usage, while vibration-based monitoring techniques (VBMT) have proved useful for the detection and localization of structural damages, which maybe are far from the location of sensors. But the current VBMT needs to be improved for the composite fuel tanks because the fluid in a tank may change the dynamic properties of the whole mechanical system.

In this paper, an experiment is designed to study the validity of vibration-based damage detection techniques with inclusion of the filled-in fluid impact on the tank. Based on the study results, the following conclusions are derived:

1) From the direct results of modal identification, it is hard to determine if the damage happed or not. Therefore, a subspace-based damage detection algorithm is proposed to implement the concerned work. The detailed theory foundation and operating procedures are described in this paper. The results of damage detection indicate that the algorithm is able to identify the damage in the structure.
2) These results are encouraging, but it should be pointed out that the continuous change of the mass of fluid filled in the structure will lead to the time-dependent parameter structure. Thus, further investigations in laboratory and/or field tests are recommended to justify the time-dependent dynamic properties of the tanks. Actual data acquisition corresponding to a wide range of operational and environmental cases should be an essential part of the future studies.

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