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14. ABSTRACT

Damage detection in engine bladed disks is often performed through ultrasonic and eddy current techniques that are reliable, but expensive and lack in-situ monitoring capability. Alternatively, vibration-based damage detection methods are relatively inexpensive, have real-time in-situ potential, but are generally inaccurate due to low sensitivity. The goal of this research is to advance the state-of-the-art of vibration-based damage detection of bladed disks by utilizing the unique vibration localization characteristics of such periodic structures to enhance damage detection sensitivity and robustness through piezoelectric circuitry networking. In this research, we have explored an innovative piezoelectric circuitry networking methodology that can temporarily amplify the damage effect on the system vibratory signature during the inspection stage. Methods for network parameter synthesis to maximize sensitivity have been established. Fundamental understandings of vibration energy propagation/distribution in bladed disks without and with piezoelectric circuitry are pursued. Monte Carlo simulations are performed to evaluate the network's effectiveness. Multivariate statistical analysis tools are synthesized that can quantify the detection performance enhancement under noise/variances.

15. SUBJECT TERMS

Piezoelectric circuitry, structural damage detection, bladed disks, periodic structures

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Highly Sensitive and Robust Damage Detection of Periodic Structures with Piezoelectric Networking

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Final Report (December 15, 2006 to May 31, 2008)

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Objectives

Damage detection in engine bladed disks is often performed through ultrasonic and eddy current techniques that are reliable, but expensive and lack in-situ monitoring capability. Alternatively, vibration-based damage detection methods are relatively inexpensive, have real-time in-situ potential, but are generally inaccurate due to low sensitivity. The goal of this research is to advance the state-of-the-art of vibration-based damage detection of bladed disks by utilizing the unique vibration localization characteristics of such periodic structures to enhance damage detection sensitivity and robustness through piezoelectric circuitry networking.

Summary of Efforts

In this research, we have explored an innovative piezoelectric circuitry networking methodology that can temporarily amplify the damage effect on the system vibratory signature during the inspection stage. Methods for network parameter synthesis to maximize sensitivity have been established. Fundamental understandings of vibration energy propagation/distribution in bladed disks without and with piezoelectric circuitry are pursued. Monte Carlo simulations are performed to evaluate the network's effectiveness. Multivariate statistical analysis tools are synthesized that can quantify the detection performance enhancement under noise/variances.

Descriptions of Accomplishments/New Findings

The proposed research is to create novel piezoelectric circuitry networking methodology such that the damage effect on the system vibratory signature can be amplified during inspection. This will cause the system response to be much more sensitive with respect to damage occurrence and will enable robust detections. This is a collaborative program with the participation of Penn State (PI: K. W. Wang) and UConn (PI: J. Tang) researchers. To achieve the project goal, the research efforts have been formulated with two major parts:

Part I: Piezoelectric network analysis and parameter synthesis for damage detection enhancement in mistuned periodic structures

Bladed disks, belonging to a special class of structures called periodic structures, have unique characteristics in dynamic responses. Ideal periodic structures have identical substructures, and the vibration energy is distributed evenly through all substructures. However, realistic periodic structures are subject to mistuning, i.e., differences between the properties of the substructures such as mass, stiffness, and geometry. When mistuning occurs in bladed disks, vibration energy can be localized around individual blades, leading to increased stress and potential for damage.

It is known that changes in the inter-blade coupling and the mistuning have the greatest effects on the wave reflections which lead to vibration localization. Thus, some studies, assuming the inter-blade coupling to be fixed, have investigated the effects of intentionally mistuning the bladed disk to alleviate forced vibration localization by creating wave reflections and effectively altering the inter-blade coupling characteristics. Similarly, it is expected that intentional mistuning can alter the system dynamics to potentially allow more sensitive vibration-based damage detection. However, intentional *blade* mistuning with fixed design may not be able to improve damage detection sensitivity while maintaining reduced forced vibration localization.

Piezoelectric circuitry networks have been studied previously for applications in vibration delocalization and vibration suppression of bladed disks. The purpose of the network is to absorb vibration energy in electrical form, due to the resonant circuitry and electro-mechanical coupling, and to form another energy propagation channel by coupling the local circuitry via capacitors. Due to its tunable components, the piezoelectric circuitry network can be utilized and adapted to achieve the tasks of both damage detection enhancement and vibration suppression.

The frequency response functions (FRFs) of a bladed disk normally contain bands of resonant frequencies of the mechanical structure. For simplicity, the blades are modeled by assuming one local beam mode so that the discretized bladed disk model contains single degree-of-freedom substructures and only one frequency band appears in the FRF. Addition of the piezoelectric network, which is modeled by capacitor-coupled resonant RLC circuits, introduces an additional frequency band and alters to original bladed disk band. The location of this additional band is primarily determined by the inductance tuning. When the frequency bands are well-separated, the bands can be distinguished as "electrically dominant," where the characteristics are dominated by circuitry parameters, and "mechanically dominant," where the characteristics are dominated by mechanical parameters. When the frequency bands are not well-separated, such dominance is indistinguishable and the frequency bands have greater similarity. For damage detection, it is not necessary to enhance the damage sensitivity of the mechanical signatures of both frequency bands. The circuitry should be introduced so the frequency bands are well-separated but mechanical signatures of the "electrically dominant" modes are still significant. The circuitry tunings can thus effectively alter the mechanical signature of the modes in the "electrically dominant" frequency band.

To investigate the damage detection sensitivity, it is necessary to use a damage index. Here, the damage index is developed by considering the ratio of the FRFs of the healthy and damaged structures. For instance, when j refers to the blade number and i to the frequency, then the healthy vibration amplitude is $X_{i,j}^{(h)}$ and the damaged vibration amplitude is $X_{i,j}^{(d)}$. Thus, the damage index is

$$D = \max\left[\max_{all\, i,j}\left(\frac{X_{i,j}^{(h)}}{X_{i,j}^{(d)}} \right) \quad \max_{all\, i,j}\left(\frac{X_{i,j}^{(d)}}{X_{i,j}^{(h)}} \right) \right] \tag{1}$$

To investigate the merit of the piezoelectric circuitry network, two cases of mistuned bladed disks are considered, one with low blade coupling and one with high blade coupling as shown in Figure 1. In each case, changes of the circuitry coupling and standard deviation of random intentional circuitry mistuning are considered. Each point is calculated by Monte Carlo simulation considering 50,000 different realizations of random blade mistuning and random intentional circuitry mistuning. From these realizations, the 5th percentile is used to characterize the performance of the worst cases, which indicates that 95 percent of the cases outperformed the result.

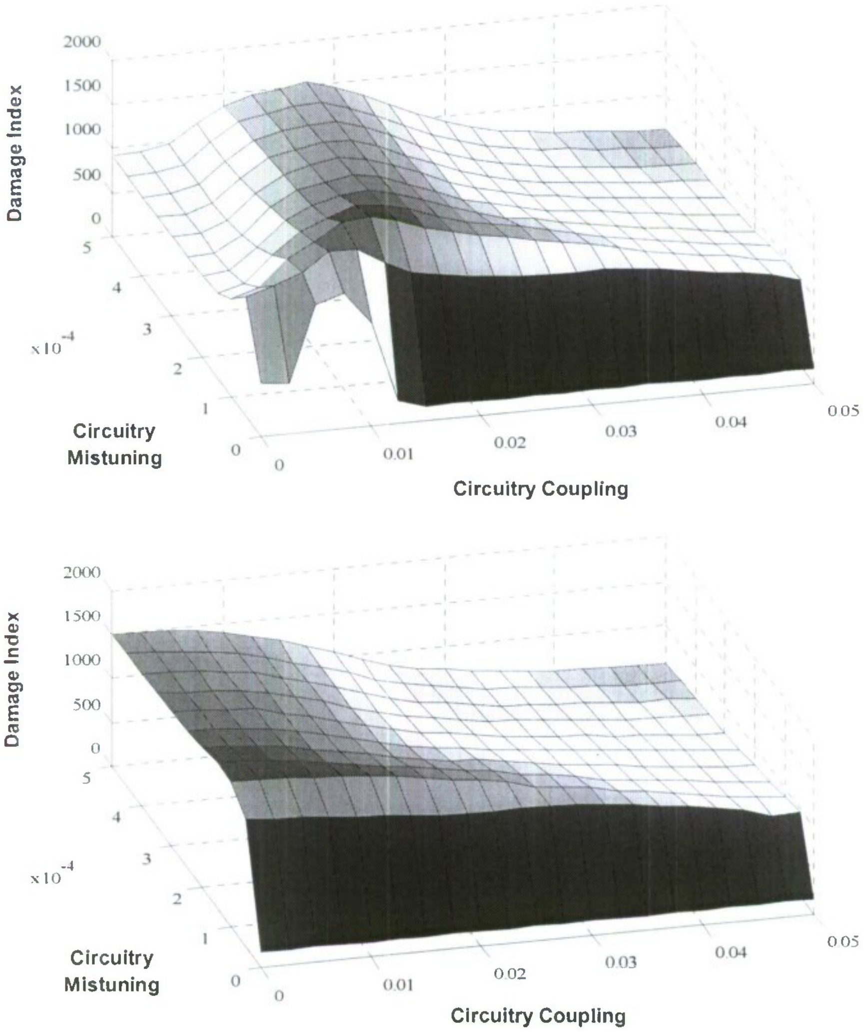

Figure 1: Monte Carlo simulations for damage detection.
Both consider n = 12, E = 1, σ_{blade} = 0.1%, κ_d = 1%, δ = 0.1, ξ = 0.1, ζ_c = 0.0001, ζ_r = 0.
[top] Low coupling, R_c = 0.08. [bottom] High coupling, R_c = 0.2.

When compared with the median damage indices for the original system without the circuitry, which are 75.3 for the low coupling case and 35.4 for the high coupling case, Figure 1 shows the improvement due to the circuitry (Note that higher index value indicates more sensitive to damage). For the low coupling case, using both intentional circuitry mistuning and circuitry coupling yield the best result. For the high coupling case, using some intentional circuitry mistuning improves the result while additional circuitry coupling reduces the index.

Part of the improvement may be explained by the effect of anti-resonances. Individual cases of mistuned bladed disks indicate that a large damage index can be obtained when a damage index ratio is taken at a frequency that is resonant in the damaged (or healthy) case and anti-resonant in the healthy (or damaged) case. Such an index is more likely to occur in a moderately coupled system, as shown in Figure 2. The results in Figure 1 show similar results. For the weakly coupled bladed disk, adding circuitry coupling increases the overall substructural coupling. Therefore, the system could be tuned to a moderately coupled region where the damage index is increased. However, for the strongly coupled bladed disk, additional circuitry coupling does not improve the result because the inter-blade coupling is already high.

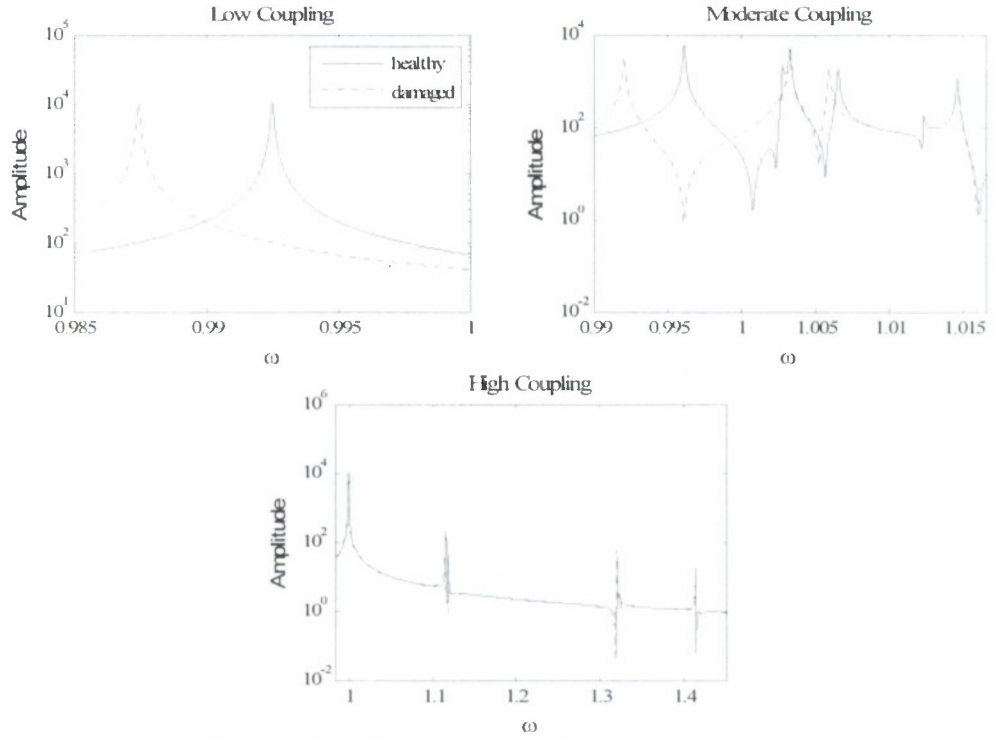

Figure 2: Individual cases of healthy and damaged structures.

Part II: Development of robust feature extraction and decision making strategy for damage detection using vibratory response under uncertainty/noise

To specifically address the significant measurement noise and system variation (e.g., mistuning) in bladed disk damage detection, we have developed a multivariate statistical analysis procedure for effective de-noising and decision-making. A Principal Component Analysis (PCA) based approach has been formulated for feature extraction and de-noising of the vibration responses that can take full advantage of the response anomaly amplification owing to the piezoelectric networking, followed by a Hotelling T^2 statistic analysis to examine the conformity of the response patterns before and after damage occurrence with confidence level. The data to be used for damage detection are the forced response of bladed-disk under frequency sweeping that, in actual systems, can be measured by using blade-tip-timing (BTT) technology. Such response data are subject to system variation (mistuning) and measurement noise.

Principal component analysis (PCA) is a multivariate statistical analysis method for variance analysis. The use of PCA allows the original multivariate data set in a k-dimensional space to be transformed into a new set of uncorrelated variables, the so-called principal components (PCs), in an *n*-dimensional space where $n < k$. Therefore, dimensionality reduction can be achieved, while major features in the data set is extracted. Meanwhile, the minor features can be considered as the contribution of the noise/uncertainty and signal denoising can be achieved by eliminating such contribution.

In order to perform PCA based feature extraction, we need to establish the baseline data using the forced response of the healthy engine bladed-disk. We collect multiple observations of the forced response of individual blade under a complete frequency sweep (during spin-up or spin-down). Using these available forced response data, we can form a matrix $X = [x_{ij}(\omega)]$ which has m rows of responses (*i.e.*, m observations), each with k frequency points or spectral lines. The first step of PCA is the "auto-scaling", where each column of the measurement data X will be adjusted to have a zero mean with unit variance, which yields a response variation matrix $\tilde{X}$. By definition, the principal components (PCs) are the eigenvalues and the corresponding eigenvectors of the covariance matrix. The first few PCs, *i.e.*, the highest eigenvalues and the corresponding eigenvectors, represent the direction and amount of maximum variability in the original data. In other words, the most significant PCs contain those features that are dominant in the BTT measurements. It follows that the random noise, which is not correlated with such global features, is represented by the less significant components. Thus, reconstructing the response by using the highest PCs only should not only achieve data compression but also remove some of the noise. Usually a handful of PCs (corresponding to the first few eigenvalues) will suffice to characterize the variation in the baseline signals, constituting a *feature space* with much lower dimension. The rest of PCs can then be considered as the contribution of the noise and be discarded for denoising. At the inspection/detection stage, one obtains a new forced response signal (or referred to as new observation) using real-time BTT sensing during engine spin-up or spin-down. This new complete observation $(\mathrm{x}_{new})_{1\times k}$ will undergo the aforementioned auto-scaling to yield $(\tilde{x}_{new})_{1\times k}$. This response variation matrix $(\tilde{\mathrm{x}}_{new})_{1\times k}$ will then be projected onto the k principal components. The projection matrix A and the eigenvector matrix P can be partitioned into two sub-matrices with n principal components (corresponding to major features) and $k-n$ principal components (corresponding to noise/uncertainty), respectively. The signal denoising is facilitated by the eigenvector truncation, *i.e.*,

$$(\tilde{\mathrm{x}}_R)_{1\times k} = AP^T = ((A_1)_{1\times n} \,|\, (A_2)_{1\times(k-n)})((P_1)_{k\times n} \,|\, (P_2)_{k\times(k-n)})^T \approx (A_1)_{1\times n}(P_1)^T{}_{n\times k} \tag{2}$$

To compare the new reconstructed signal $(\mathrm{x}_{new})_R$ with the baseline signal x which is the mean response of the m observations of the healthy structure, the directionality is defined to describe the difference between them, which can be expressed as

$$Dir = \sin^{-1}\left(\left\langle(\mathrm{x}_{new})_R \cdot (\mathrm{x})_{baseline}\right\rangle / \left\langle(\mathrm{x})_{baseline} \cdot (\mathrm{x})_{baseline}\right\rangle - 1\right) \tag{3}$$

where $\langle\cdot\rangle$ denotes the inner product. Clearly, the reconstructed forced response of a healthy bladed-disk, whose deterministic features are the same as those of the baseline, will show high degrees of conformity with the baseline. On the other hand, the response of a damaged bladed-disk, whose deterministic features have notable discrepancy from those of the baseline, will exhibit significant change after reconstruction.

In this research, the feature comparison is facilitated by using the Hotelling T^2 statistic. We consider a p-variable problem with each variable having m observations. Let the mean vector and the sample covariance matrix be $\bar{x}$ and S, respectively. The covariance matrix S indicates the relationship among the p-variables. In the present study, the directionality analysis result (Equation (3)) of blade response is used for damage detection. Therefore, the directionality results calculated at p sub-groups will be used in the analysis and we need to calculate their mean and covariance. Recall that in order to deal with the system uncertainties/noise, the bladed-disk will be measured multiple times to establish the baseline. There are two distinct phases involved in constructing the Hotelling T^2 control limits. First, we use the aforementioned m observations of the healthy bladed-disk to establish a Phase I baseline and an upper control limit under a specified confidence level. The purpose is to examine the baseline data and the relation of healthy condition with respect to the upper control limit. For a given set of directionality analysis result d_k, the statistic T^2 is defined as

$$T^2 = (d_k - \bar{d})^T S^{-1} (d_k - \bar{d}) \tag{4}$$

It can be proved that the statistic T^2 follows the F-distribution. Therefore, under a given Type I error probability α, the Phase I upper control limit $\mathrm{UCL}^{\mathrm{I}}_{p,m,\alpha}$ can be established as

$$\mathrm{UCL}^{\mathrm{I}}_{p,m,\alpha} = \frac{p(m-1)^2}{m(m-p)} F_\alpha(p, m-p) \tag{5}$$

where $F_\alpha(p, m-p)$ is the $1-\alpha$ percentile of the F-distribution with p and $m-p$ degrees of freedom. Indeed, we may use m observations of the directionality analysis results of forced responses of the healthy bladed-disk to establish a control limit with $1-\alpha$ confidence level.

The baseline data of the healthy bladed-disk will then be utilized to establish Phase II statistic T^2 for damage detection. Since the new response measurement and its directionality analysis is independent of the Phase I baseline, the Phase II upper control limit is modified as

$$\mathrm{UCL}^2_{p,m,\alpha} = \frac{p(m-1)(m+1)}{m(m-p)} F_\alpha(p, m-p) \tag{6}$$

In other words, after we obtain a real-time measurement of the blade response, we use Equation (3) to calculate the directionality and then use Equation (6) to calculate its statistic T^2 value. If this value exceeds the Phase II upper control limit that we have established by using Equation (6), we may conclude, with $1-\alpha$ confidence level, that the blade response is abnormal and damage has occurred.

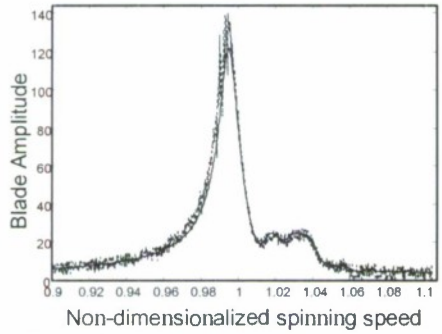

Figure 3. Undamaged blade response (solid line) and reconstructed damaged response (dashed line, 0.5% damage)

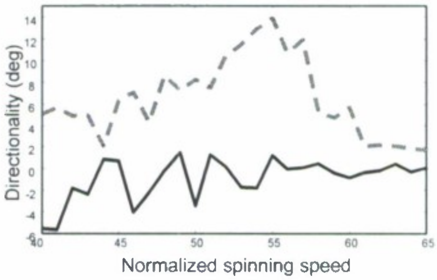

Figure 4. Feature difference of undamaged (solid line) and damaged (dashed line) blade responses.

The robust and quantitative decision making approach has been examined extensively using simulated data. A representative analysis is reported in what follows. We assume the blade has 1.25% mistuning (i.e., variance of first natural frequency), and the measurement is subject to 10% noise. We first consider a strong coupling $R = 0.3$ (R is the ratio of the coupling stiffness to the blade modal stiffness). The undamaged and damaged blade responses are plotted in Figure 3, where the damage causes 0.5% change of one blade. While the difference between the responses are extremely small, after carrying out the PCA process the feature differences are highlighted, as shown in Figure 4. Here the feature difference corresponding to the damaged response is consistently greater than zero, indicating anomaly.

We then use the Hotelling statistic analysis to quantitatively analyze the feature difference. It can be seen from Figure 5 that the T^2 statistic clearly exceeds the control limit (corresponding to 95% confidence level).

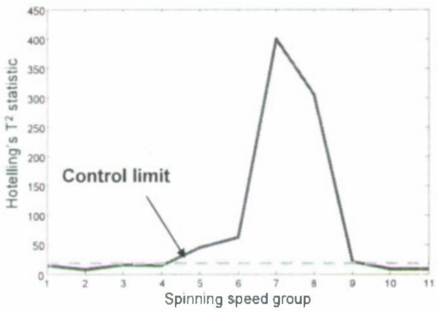

Figure 5. T^2 statistic analysis result of 0.5% damaged response under strong coupling R=0.3.

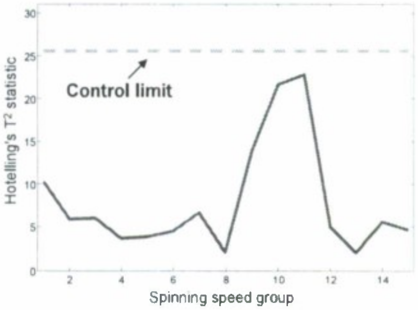

Figure 6. T^2 statistic analysis result of 0.05% damaged response under strong coupling R=0.3.

To investigate the effects of coupling and vibration localization enhancement to the damage detection sensitivity, we compared the detection results under different damage severity with different coupling level. Plotted in Figure 6 is the detection result of a 0.05% blade damage under strong coupling. The damage effect is buried in the mistuning/uncertainty, and the T^2 statistic cannot indicate the damage occurrence. After the coupling level is reduced to R=0.05, under the same mistuning/uncertainty, this 0.05% damage becomes detectable (Figure 7). Clearly, with the reduction of the inter-blade coupling and the localization enhancement, the sensitivity of vibration-based damage detection in periodic structures is greatly improved.

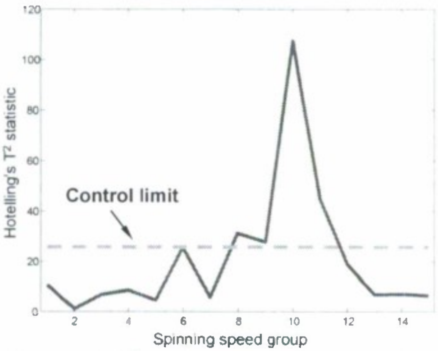

Figure 7. T^2 statistic analysis result of 0.05% damaged response under reduced coupling R=0.05 with localization enhancement.

Personnel Supported

Other than the PIs, Drs. K. W. Wang and J. Tang, the project has involved two Ph.D. students (Ryan Struzik and Ji Zhao).

Publications

Struzik, R.C., and Wang, K.W., "Intentionally mistuned piezoelectric networks for the enhancement of bladed disk structures," SPIE Smart Structures Conference, 2009 (to appear).

Zhao, Ji, and Tang, Jiong, "Changing dynamic behavior of periodic structure using piezoelectric circuitry," SPIE Smart Structures /NDE, V 7288, 2009 (to appear).

Interactions/Transitions

This research is very relevant to AFOSR's mission, since the results can be applied to various Air Force systems, such as space structures, satellite antennae, and bladed-disk assemblies (e.g., fans and compressors) in gas turbine engines.

The PIs have had various interactions and technical discussions with Dr. Charles Cross and other researchers at the Wright-Patterson Air Force Research Lab (AFRL) on issues regarding fan structure implements and experimental set ups. Dr. Wang has had communications with researchers at the Kirtland AFRL. Dr. Tang has had extensive discussions with Pratt & Whitney engineers and GE Global Research Center researchers to gather engineering insights on bladed-disk dynamics and sensing mechanisms that have greatly enhanced the level of research.

Honors/Awards

Dr. K. W. Wang has been the holder of the Diefenderfer Chair in Mechanical Engineering at Penn State, and now the holder of the Stephen P. Timoshenko Collegiate Chair in Mechanical Engineering at the University of Michigan. Dr. Wang is a Fellow of the ASME and is the recipient of the 2007 ASME N. O. Myklestad Award for major innovative contribution to vibration engineering and the 2008 ASME Adaptive

Structures and Materials System Prize for significant contributions to the advancement of the sciences associated with adaptive structures and/or material systems.