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DAMPING MEASUREMENTS USING OPERATIONAL DATA

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ABSTRACT

We have measured modal damping using strain-gauge data from an operating wind turbine. Previously, such measurements were difficult and expensive. Autocorrelation and cross-correlation functions of the strain-gauge data have been shown to consist of decaying sinusoids which correspond to the modal frequencies and damping ratios of the wind turbine. We have verified the method by extracting damping values from an analytically generated data set. Actual operating response data from the DOE/Sandia 34-meter Test Bed has been used to calculate modal damping ratios as a function of rotor rotation rate. This capability will allow more accurate fatigue life prediction and control.

INTRODUCTION

The production of efficient and inexpensive wind turbines will require larger and lighter structures. These characteristics will increase flexibility and drive the modal operating frequencies down. Therefore, knowledge of the modal damping characteristics (both structural and aerodynamic) will become increasingly important to increase fatigue life and prevent adverse responses. The inherent structural damping can be determined on parked wind turbines using conventional modal testing techniques [1,2]. Analytical methods exist to estimate the aeroelastic damping for stationary and rotating wind turbines in the range of linear aerodynamics [3]. However, experimental results are needed to verify and/or upgrade the analysis.

Carne and Nord have developed methods for performing modal testing of rotating wind turbines [4]. These techniques are expensive, require specialized equipment, and require low winds. Consequently, it is desirable to estimate modal parameters of the operating turbine without special equipment. Previously, ambient wind excitation has been used to obtain modal frequency estimates [1]. Lauffer has also calculated modal damping from a parked wind turbine undergoing ambient wind excitation [5].

The goal of this effort is to find a viable technique for calculating damping ratio versus turbine rotation rate for each mode of interest. This paper begins by providing a description of the method used. The method is verified using analytically generated data. The techniques are then applied to operational strain gauge data from the DOE/Sandia 34-meter Test Bed. And finally, conclusions and recommendations are presented.

DESCRIPTION OF METHOD

Conventional modal analysis utilizes Frequency Response Functions (FRF) which require measurements of both the input force and the resulting response; however, ambient wind excitation does not lend itself to FRF calculations because the input force can not be measured. Auto and cross-correlation functions are commonly used to analyze randomly excited systems. These functions contain decaying sinusoids representative of the structure's modal frequencies and damping ratios. Therefore, time domain modal identification schemes can be used to estimate the modal parameters by treating the auto and cross-correlation functions as free vibration responses. Common schemes include the Polyreference technique [6], the Eigensystem Realization Algorithm (ERA) [7], the Ibrahim Time Domain (ITD) method [8,9], and the Maximum Entropy Method (MEM) [10,11].

A set of the strain-gauge output channels to be used in the modal extraction process was defined. These strain-gauge signals were treated as outputs in the modal extraction process. A subset of these strain gauge output signals, which collectively contained all the modal frequencies of interest, were chosen as inputs or references in the modal parameter extraction process.

The Fourier transform of each strain time history was calculated. The cross-spectrum (or auto-spectrum) of the time history from each response with respect to each reference location was calculated. Each spectrum was averaged over several data sets. The cross-correlation (or auto-correlation) functions were then generated by taking the inverse Fourier transform of the averaged spectra. The Polyreference method [6] was used to analyze this set of auto-correlation and cross-correlation functions by treating them as averaged free vibration responses. Lauffer, et. al. in [5] had previously explored the use of this technique for data from a parked wind turbine.

The identified modal frequencies and damping ratios were used to resynthesize the auto-spectra of the averaged response at each output location. A least-squares differential correction technique [12] was used to solve for the modal scale factors or residues necessary for this resynthesis. This provided a means of visually verifying the estimated natural frequencies and damping ratios.

VERIFICATION OF METHOD

Dohrman's VAWT-SDS code [13] was used to generate the time history response of a rotating vertical axis wind turbine undergoing aerodynamic forcing. Results were generated for the DOE/Sandia 34-meter Test Bed using a 30 rpm rotation rate, 20 mph winds, and a 15% turbulence intensity. The selected set of response locations, shown in Figure 1, included lead-lag and flatwise responses at the top of blade 1 (location 1A), the middle of blade 1 (location 1H), and the bottom of blade 1 (location 1Q), as well as, an in-plane and out-of-plane response on the tower (location TS). Ten time histories, with similar wind conditions, were generated using a step size of 0.04 seconds and a data length of 2048 steps. Stiffness proportional damping, sufficient to produce a damping ratio of 0.2% at 1.4 Hz, was added to the model. Sensor noise was simulated by adding a white noise signal with a standard deviation which was 2% of the standard deviation of each generated time history.

Table 1 contains the results of the modal parameter calculations. Column 1 contains the name and description of the mode shape (plots of these mode shapes are available in [14]). Column 2 contains the analytical modal frequency and column 3 the analytical modal damping ratio. The analytical modal frequencies were calculated by extracting the complex eigenvalues from the structural matrices used in the VAWT-SDS code. The approximations inherent in numerical integrations produce period elongations in the integrated results [15]. The frequency shifts created by the numerical integration were calculated and a correction was added to the modal frequency and modal damping results. The damping ratios do not attempt to model reality, but provide specified damping levels as a means of verifying this modal estimation technique. Column 4 contains the modal frequencies as calculated using the Polyreference technique and column 5 the corresponding modal damping ratios.

Generally, the agreement between the VAWT-SDS specified damping ratios and the calculated damping ratios is good with a few exceptions. Some torsional damping was added to the model which increased the damping in the propeller modes. This caused the amplitude of the third propeller mode to be low enough to avoid detection. The modal frequencies and damping ratios for the first symmetric and antisymmetric flatwise modes were not determined as accurately as other modes. These modes are very closely spaced and difficult to extract as a result. The higher modes have calculated modal damping ratios that are lower than specified. The amplitudes of these modes are very low compared to the noise level, which adversely affected these estimates.

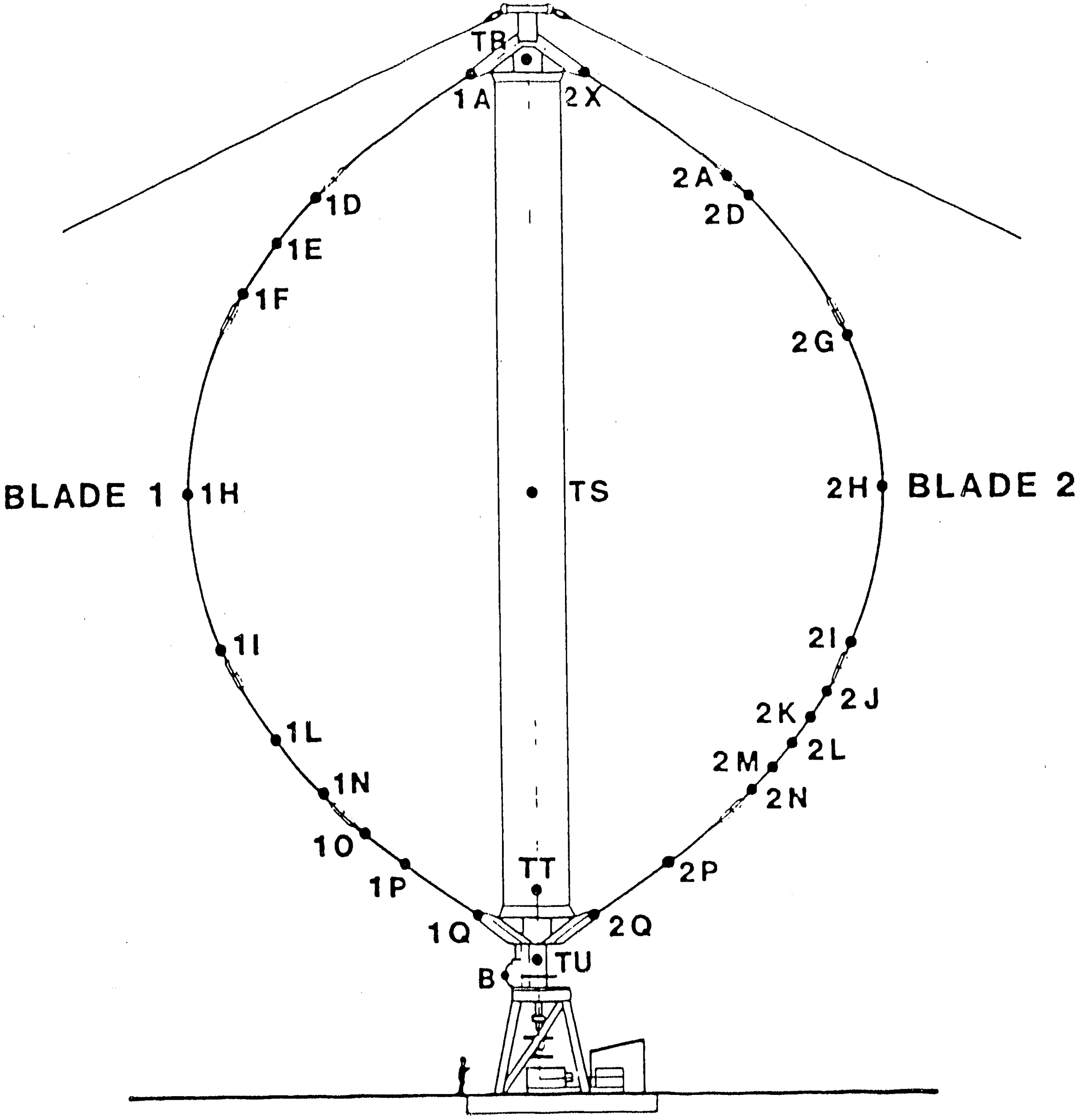

Figure 1. DOE/Sandia 34-Meter Test Bed Strain Gauge Outputs

Table 1. Comparison with Analytical Results

	Specified by VAWT-SDS		Calculated by Polyreference	
Mode Description	Frequency (Hz)	Damping (%)	Frequency (HZ)	Damping (%)
$1F_a$-1st Flatwise (Antisymmetric)	1.27	.19	1.31	.35
$1F_s$-1st Flatwise (Symmetric)	1.35	.20	1.32	.34
1B-1st Blade Edgewise	1.59	.25	1.59	.29
$1T_i$-1st Tower In-Plane	2.02	.31	2.01	.38
$2F_s$-2nd Flatwise (Symmetric)	2.43	.38	2.44	.50
$2F_a$-2nd Flatwise (Antisymmetric)	2.50	.35	2.50	.38
$1T_o$-1st Tower Out-of-Plane	2.80	.31	2.80	.52
$2P_r$-2nd Rotor Twist	3.39	.51	3.39	.59
$2T_i$-2nd Tower In-Plane	3.46	.50	3.45	.44
$3F_a$-3rd Flatwise (Antisymmetric)	3.65	.49	3.63	.36
$3F_s$-3rd Flatwise (Symmetric)	3.73	.59	3.73	.38
$3P_r$-3rd Rotor Twist	3.74	.98	-	-
2B-2nd Blade Edgewise	3.88	.49	3.87	.34

The one per rev harmonic (0.5 Hz), the two per rev harmonic (1.0 Hz), and the three per rev harmonic (1.5 Hz) were found in the data as expected. No higher harmonics were distinguishable in this data. Apparent damping ratios for these harmonics were calculated automatically. However, these quantities do not have physical meaning.

Figure 2 presents the auto-spectrum of the lead-lag output at the bottom of blade 1 (1Q of Figure 1). The solid line is the analytical data produced by the simulation code VAWT-SDS. The dotted line is the auto-spectrum resynthesized using the Polyreference extracted parameters. It is clear that the modal frequencies were accurately identified. The correct

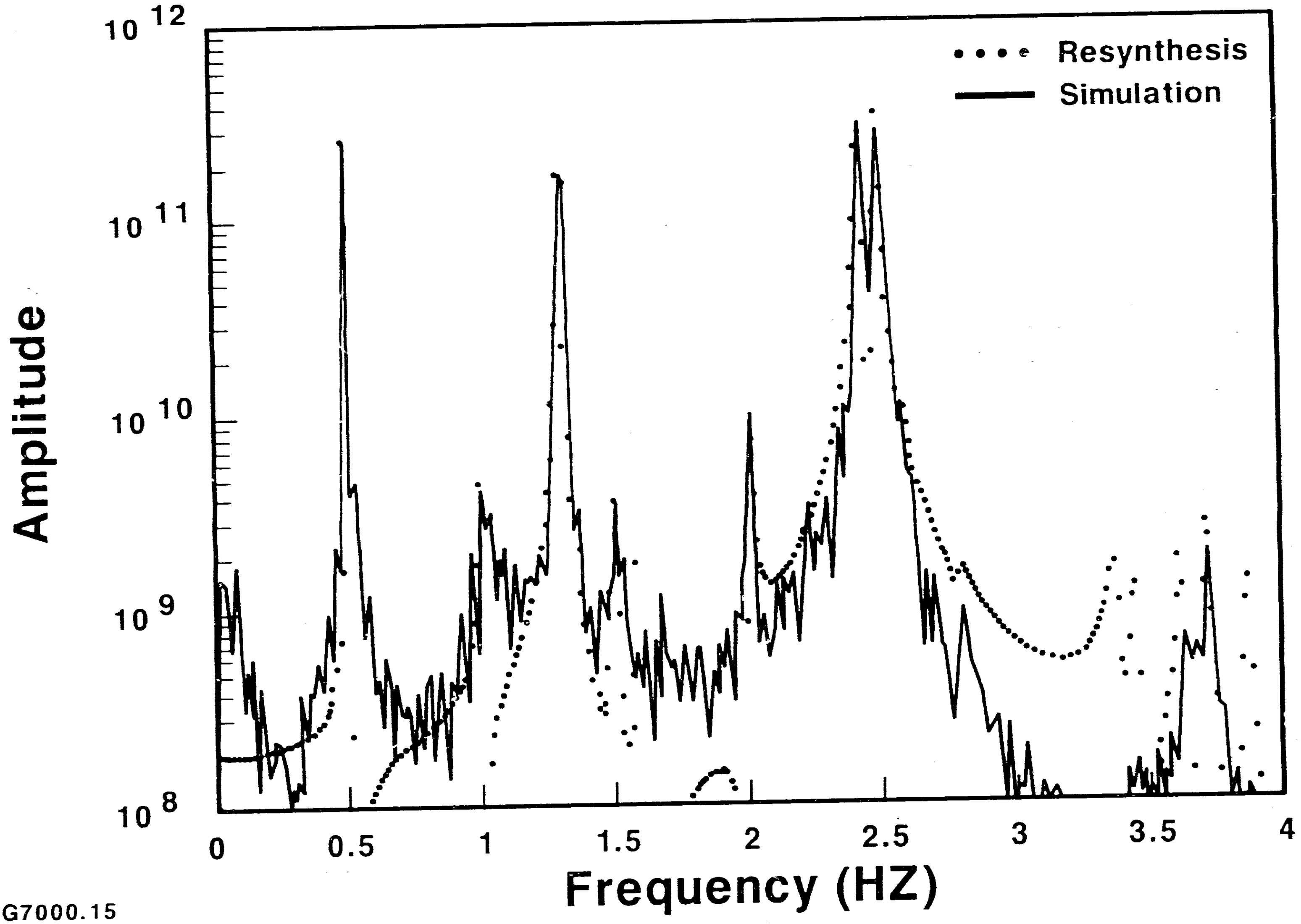

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Figure 2. 30 rpm VAWT-SDS Simulation Results for Lead-Lag Output at Location 1Q Including 2% Added White Noise (Auto-Spectrum)

reconstruction of the peaks with the largest amplitudes provides an excellent indication that the modal damping was estimated accurately. The lower amplitude peaks were not reconstructed as well, due to added sensor noise, inherent randomness of the input, and numerical round-off. The ability of this method to reproduce known modal frequencies and specified damping levels lends confidence for its application to field data. The next section exercises the same techniques with actual operating environment data.

APPLICATION OF METHOD

Currently, ambient wind-excited tests of the 34-meter Test Bed are available at rotation rates of 10, 15, 20, 28, 34, and 38 rpm. Long duration time histories of approximately 30 minutes have been taken at a sampling rate of 20 Hz. Akins' CSPEC software [16] was used to calculate averaged cross-spectra of these time histories using 1024 data point blocks. The desired cross-correlation functions were calculated by taking the inverse Fourier transforms of these cross-spectra.

This paper reports results from tests at rotation rates of 10, 15, and 20 rpm. Responses at six strain-gauge locations were used including a lead-lag and a flatwise strain gauge at each of the following locations (see Figure 1): top of blade 1 (1A), bottom of blade 1 (1Q), and top of blade 2 (2X). The lead-lag and the flatwise outputs at the top of blade 1 (1A) were used as reference locations. As with the analytical data, the Polyreference method was used to estimate modal frequencies and damping ratios from the averaged correlation functions.

Table 2 provides the modal frequencies and modal damping parameters recovered from these tests. The strain-gauge locations chosen were not sensitive to the first tower in-plane and the first tower out-of-plane modes, which explains the absence of these modes from the data set. The flatwise modes have higher damping values than the other modes. This was predicted in reference [3] and observed in [5]. The first flatwise modes could not be separated as observed in [5]. The 15 rpm data was expected to have the second flatwise modes and the first tower in-plane mode very closely spaced and highly coupled. This probably caused the first tower in-plane mode to be driven to a higher amplitude and thus appear in the data. It should be noted that the modes presented in this work were identified by frequency only. Proper identification of the modes should be performed by using the mode shapes as well.

Table 2. Experimental Results

	10 RPM		15 RPM		20 RPM	
Mode	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1F	1.05	2.8	1.11	3.3	1.16	3.4
1B	1.86	.5	1.78	.4	1.68	.5
$2F_a$	2.07	2.8	2.09	3.5	2.35	1.6
$2F_s$	2.18	1.1	2.38	1.6	2.29	2.2
$1T_i$	-	-	2.28	.5	-	-
$1T_o$	-	-	-	-	-	-
$2P_r$	3.52	.5	3.53	.5	3.55	.3
$3F_a$	3.48	1.5	3.54	1.9	3.64	1.6
$3F_s$	3.53	1.7	3.61	1.0	3.68	1.8

The auto-spectrum of each output was resynthesized using the estimated modal frequencies and modal damping ratios. Figure 3 shows such a comparison for the lead-lag output at location 1Q (bottom of blade 1) from the 20 rpm data. The solid line denotes the actual data, while the dotted line is the resynthesized data. The results are very encouraging. The per rev harmonics (0.33, 0.67, and 1.00 Hz) dominate the spectrum. These large amplitude, well separated peaks were reconstructed correctly. Large amplitude modal peaks were also reconstructed correctly indicating the accuracy of the modal frequency and modal damping ratio estimates. A four per rev harmonic is seen at 1.33 Hz but was missed in the identification. The 2F modes at 2.3 Hz were of low amplitude and therefore difficult to fit in the resynthesis.

CONCLUSIONS

Summary

A technique for estimating modal damping using strain-gauge data from an operating wind turbine has been developed, validated using analytical data, and successfully applied to data from the 34-meter Test Bed. The technique was initiated by calculating auto-correlation and cross-correlation functions from strain-gauge time histories. The Polyreference method was then used to extract the modal parameters from the correlation functions. However, other time domain parameter-estimation procedures could have been used.

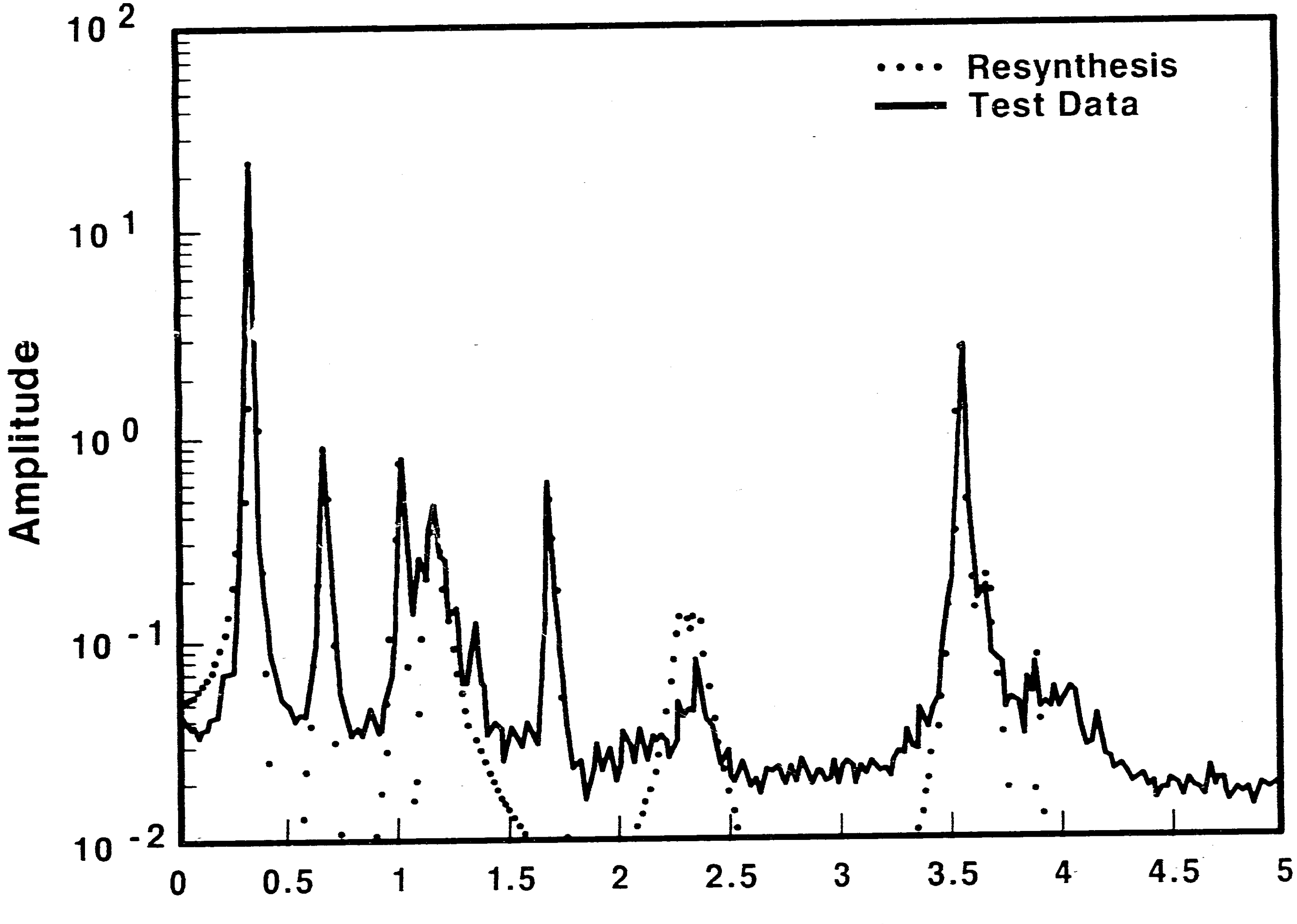

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Figure 3. 20 rpm Experimental Results for Lead-Lag Output at 1Q (Auto-Spectrum)

Previously, the calculation of modal parameters under operating conditions was difficult and expensive. The method presented in this paper has removed this restriction. The dependence of the modal damping on operational parameters can now be studied. Some parameters of interest include turbine rotation rate, wind speed, blade surface contamination, or various structural parameters. Such measurement capability will enhance the theoretical description of aeroelastic damping. Also, the techniques developed in this work could be applied to horizontal axis wind turbines.

Recommendations

Several recommendations for future work can be listed:

1). Some form of mode-shape comparison for proper identification of the modes should be used. This would require generation of analytical strain eigenvectors and extracting mode shapes from auto-spectra and cross-spectra;
2). A more optimal set of strain gauge outputs should be chosen to provide information on the tower modes;
3). Higher rotation rate data should be analyzed to complete the data base and to capture the trends;
4). The change in modal damping ratio versus wind speed (or tip speed ratio) should be studied;
5). Other time domain alogrithms such as ERA, ITD, or MEM should be used to assure algorithm independent answers;
6). The extracted damping levels should be compared to analytical damping estimates to upgrade theoretical predictions; and
7). The technique should be applied to horizontal axis wind turbines.

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