Aspects of Health Monitoring for Cable Stay Bridges

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INTRODUCTION

Cable stay bridges offer new design and monitoring challenges for engineers. These bridges incorporate both well understood structural elements such as steel and pre-stressed concrete and newer/less well understood structural elements such as cable stays. The long, flexible stays are a vital part of the load path on these structures, and are subject to wind, rain, and traffic-induced vibration. These vibrations, when excessive, can lead to service and maintenance issues for the structure. These same vibrations can also be used to measure cable tension, a key design parameter. In this paper we describe our work to date in quantifying cable tension through the use of vibration measurement techniques.

MOTIVATION AND BACKGROUND

At the present time, the Ohio Department of Transportation (ODOT) is designing and building three cable stay bridges. These bridges have unique design properties and dynamic behaviours that create new challenges for health monitoring. Basic design data for these bridges is listed in Table 1.

Table 1: Ohio's Cable Stay Bridges

	US Grant	MRC	Ironton-Russell
Location	Portsmouth, OH	Toledo, OH	Ironton, OH
Design	Steel	Concrete	Steel
Number of Main Span Piers	2	1	1-2
Tower Height (ft)	289	452	533
Number of Stays	32 pairs	40	35 pairs
Deck Width (ft)	35	66	70
Cable Stayed Span Length (ft)	1685’	1225’	1740’
Monitor Size (gages)	156	166	218
Status (2005)	Construction	Construction	Design

The University of Cincinnati Infrastructure Institute (UCII), under the auspices of ODOT, is designing and implementing health monitoring systems for each of these bridges. An overview of the monitor design for the US Grant is presented in a companion conference paper [6]. Two of these bridges, The US Grant and the Maumee River Crossing (MRC), are currently under construction. The third bridge, the Ironton-Russell, is currently in design.

MECHANICS OF CABLE VIBRATION

Cable stay dynamics can be modeled using beam theory as described by Clough and Penzien [3] and expanded upon by Mehrabi [9]. The dynamics of a stay or a beam are governed by the forces acting on a

Figure 1: Designers' renditions of the US Grant, MRC, and Ironton-Russell Bridges

differential segment of the stay/beam. The physical parameters of the stay that affect the differential segment dynamics and thus also the stay dynamics include the mass per unit length and the bending stiffness. A finite difference formulation given by Mehrabi [9], and used in our research, is based upon this differential segment approach and incorporates the affects of external influences such as axial force (tension), static lateral forces like gravity, external dampers and springs, etc. and includes sag effects.

The frequency of a vibrating stay is related to its tension in much the same way that we would expect from everyday experience with vibrating strings: As the tension of a taut string increases, so does the frequency of the resulting vibrations. We can measure these frequencies and use this information to calculate the tension in the stay.

For a simplified taut string, the fundamental frequency (f_1) of this vibration is given by the following equation, as provided by Peeters, et al [10]:

$$f_1 = \frac{1}{2L}\sqrt{\frac{H}{m}}, \tag{1}$$

where is the H is the horizontal tension in the cable, L is the length of the cable, and m is the mass per unit length. Thus, we can solve Equation (1) in terms of H, and get the following equation for cable tension from the taut string model:

$$H = m(f_1 2L)^2. \tag{2}$$

Real world cable stays differ from this simple model described above in several ways. The first and most obvious is the presence of higher order harmonics. In addition to the fundamental frequency that characterizes a given level of tension, there are harmonics present that can assist in the precise determination of the fundamental frequency. Unlike a classical taut string, the harmonics of the stay are not fully linear with respect to frequency, but rather deviate slightly due to the effects of cable stiffness, damping and sag.

To correctly estimate the tension we need to take into account these differences and provide the necessary corrective measures. One of the methods currently being used is to estimate the equivalent-taut string frequencies from the measured frequencies (of the stay) using simple relationships. Unlike a taut string, the bending stiffness of a stay cable is not negligible. This can be incorporated into a better model using perturbational methods yeilding (Robert, et al) [11]:

$$\frac{f_n^{EI}}{f_n^s} = 1 + \frac{2}{\epsilon} + \frac{4 + n^2\pi^2/2}{\epsilon^2}, \tag{3}$$

where f_n^{EI} is the measured frequency of the n^{th} harmonic, f_n^s is the equivalent-taut string frequency of the n^{th} harmonic and ϵ is a dimensionless parameter related to the bending stiffness.

$$\epsilon = L\sqrt{\frac{H}{EI}}. \tag{4}$$

Research has shown that cable stays behave much like the slightly rigid taut string described above. Other authors have expanded this basic model to include the effects of damping and inclined cables [13] [14]. These higher order effects must be considered in order to perform a complete analysis, but their effect is fairly modest. Work with the finite difference model described by Mehrabi [9] suggests that these higher order effects alter the frequency of higher order harmonics by no more than 3%.

DATA ACQUISITION HARDWARE

The Nature of the Problem

Following the discussion above, cable stay tension can be derived from an analysis of various structural parameters and stay vibrational frequencies, the latter of which can be obtained from field measurements. UCII has more than a decade's worth of experience in applying modal and vibrational testing to actual highway structures, e.g., [1],[5],[7],[8]. The focus of UCII's efforts have been in the development and application of various forced excitation methods such as Multiple Reference Impact Testing wherein a structure is impacted with an instrumented hammer, and the acceleration at various locations is simultaneously measured. Both inputs and excitations are measured and can be used to derive a wide variety of modal parameters such as frequencies, mode shapes, mass participations, and flexibility.

While the possibility of using forced excitations in cable stay monitoring exists, the current approach has been to make direct measurements of the ambient-induced vibration at the site. While this simplifies the field measurements, it requires greater care in data post processing since the measurable accelerations are very small and poor signal to noise ratios can result. In some cases measurement of the fundamental frequencies have not been possible and they have been inferred these from higher harmonics.

In addition, the large size of these structures typically results in low vibrational frequencies. Most contemporary commercial data collection systems which have been designed for use at higher bandwidths (i.e., rotating machinery, etc.). As a result, most systems are over designed and not cost effective for these kinds of measurements.

However, the low frequency specifications and need to measure only frequencies in this application makes the design of custom hardware possible and UCII currently has a low cost, rugged, electronics package under development to meet these needs.

Data Acquisition Systems

At the present time, we are using our existing data acquisition systems, consisting of a VXITech/Agilent 1432A 16 channel digitizer in conjunction with a PCB 478A16 capacitive accelerometer signal conditioner and PCB 3701 (Figure 2) series capacitive accelerometers.

CURRENT STATE OF THE RESEARCH PROJECT

Availability of Structures for Testing

Of the three bridges described in our introduction, only one, the US Grant bridge in Portsmouth Ohio, is in an advanced state of construction (Figure 3). Stay vibration monitoring is only one part of a larger project that includes strain measurements in structural steel members as well as the concrete of the deck and tower [6].

Preliminary Experiments and Experimental Findings

At this time we have conducted two experiments on the partially completed US Grant Bridge. In our first experiment we measured the ambient vibration of individual strands in a partially completed cable stay

Figure 2: Accelerometers mounted on a US Grant Cable Stay (left) and Stay Sheath (right)

Figure 3: The partially completed US Grant Bridge. As viewed from the North, August 2005.

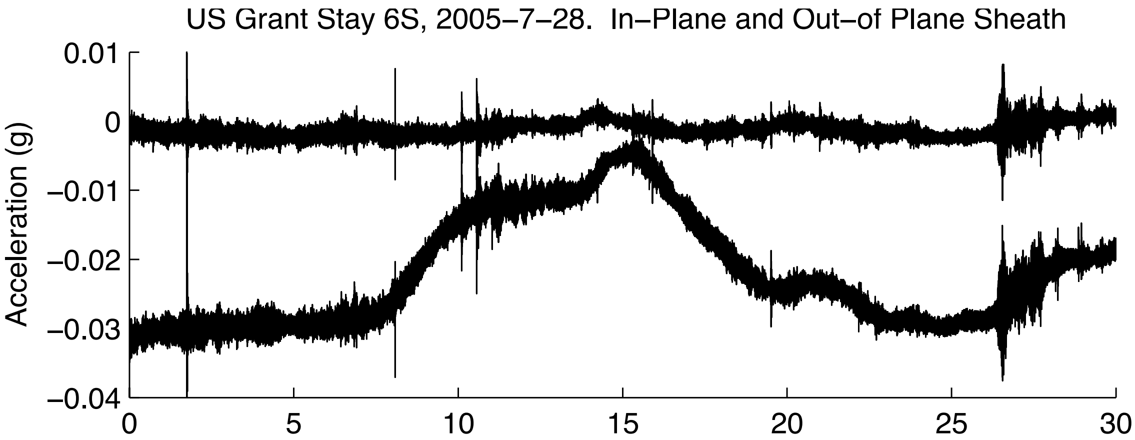

Figure 4: Sensor drift due to effect of direct sunlight on sensors. Time in Minutes

(Figure 2, left photograph). The stay was fully assembled, but had had not yet been environmentally sealed. This strand data allowed us to perform initial tests of data processing techniques on relatively pristine data.

In our second experiment, we used a horizontal deck accelerometer, a wind sensor, and four accelerometers mounted on the cable stays. We placed the accelerometers on completed stays in two different configurations (Figure 2, right photograph). In part one, we instrumented and monitored two neighboring cables simultaneously. In part two of this experiment, we instrumented the same cable with two pairs of sensors: A lower pair, mounted approximately 112 inches from the stay mounting bracket, and a second set, approximately 233 inches from the bracket. For both of these sub-experiments, we collected wind speed data to better understand the ambient excitation.

Two effects have been most visible to date as a result of our experiments on the partially constructed US Grant bridge. First, that long measurement cycles can lead to significant amounts of sensor drift (Figure 4). This drift, while large compared to the accelerations of the cable, has a large spectral separation from the stay vibration frequencies and so can be adequately controlled through good experimental design and post-processing.

Two alternatives signal processing approaches currently under consideration include: Analog filtering with high-pass active filters, and digital filtering using high order digital filters. Analog filters have the benefit of being well understood technology, but the low cutoff frequencies required can make them difficult to design. Poor thermal stability of filter components can potentially re-introduce the signal drift that we are trying to filter out, essentially moving it from the sensor to the signal conditioner. Based upon experiments with digital filtering, we have reason to believe that high order digital filtering is a good candidate for solving this problem. One complication is that the long startup times for high order digital filters mean that we must discard initial data points so that filter induced transients do not corrupt the quality of our data.

Secondly, the ambient motion of the cable is quite small. Other researchers have observed significantly larger motion with the aid of truck tests on fully assembled structures [12]. The sample data visible in Figure 4 is typical of ambient data that we have measured to date. Signal amplitudes are typically on the order of 5mV. These signal levels are uncomfortably close to the commonly accepted noise floor of 1mV. We believe that larger inputs will yield data more amenable to automatic processing and frequency extraction.

One open question at this point is the role of the stay sheath in damping measurable stay vibrations. Due to the design of the US Grants' stays, we do not have access to the individual strands after construction is complete. Each individual stay is covered by a PVC pipe that protects the stay strands from corrosion and other environmental damage. Unlike other cable stay bridges that we have identified in the literature, the stays at the US Grant bridge are not grouted. While the sheath is in direct contact with the strands at the center of the stay, that is not the case at the ground level.

Table 2: Fundamental stay frequencies predicted by different modeling/analytical methods

Taut String Analysis	3.071
Finite Difference Modeling with sag [9]	3.102
ABAQUS Finite Element Model	3.067

Preliminary Analysis of Data

Figure 5 is a typical measured spectra from an individual strand in comparison with that of the spectra measured on the sheath. We collected the data with the PCB Sensors and VXITech digitizer described above. The data was sampled using the .1V signal range at 160Hz, for an effective frequency span of 64Hz. Initial experiments contained time series about about 90s of data per test, but we have been collecting 15 and 30 minute data sets as part of our effort to determine an effective experimental method for this bridge.

The graph (Figure 5) is the average of 341 individual FFTs. It was formed by sliding a 4096 point FFT window over the data set, 32 points at a time, as described by Allemang [2] and [4].

From the graph, several things are immediately apparent: First, that there is much less spectral energy available when we measure at the sheath. Secondly, we can see that the strand data has well defined spectral peaks in comparison with the sheath data. Third, not all frequencies/harmonics can readily be ascertained by inspection from the spectra. At this point we do not fully understood the role of the stay sheath in reducing measurable stay vibration.

An Initial Estimation of Stay Tension

Stays at the US Grant are tensioned strand by strand in three phases: A first tensioning occurs during assembly of the stay, during which the first strands are tightened to varying amounts per the bridge assembly plans. After the stay is fully assembled with all strands in place, the strands are re-tensioned to equalize the load on each strand. Finally, after the bridge is fully assembled, all strands are re-tensioned to the final values dictated by the bridge design.

The strand data pictured depicted in Figure 5 was collected after the second tensioning described above. The design documents for the the bridge specify this stay as having a length of 172.2 feet, tension of 414 kips, and mass of 11.91 lbs/ft.

Using these parameters, we can analytically calculate the expected frequency using a variety of methods (Table 2). The taut string frequency was calculated using Equation (1). The Finite Difference model is described by Mehrabi [9], and is based upon a 500 segment model. The finite element frequency is based upon a ABAQUS^{TM} FE model created at UCII.

We can compare these analytic results with those obtained from stay experiments. We chose the most unambiguous frequencies from the spectrum of the single strand depicted in Figure 5. While we can calculate any harmonic described above, the fundamental frequency is the most useful for direct estimation of tension. Although the harmonics above 10Hz are clearly visible in Figure 5, the same is not true of the fundamental at 3Hz, and its harmonic at 6Hz. We have used two different techniques to determine the fundamental frequency of the stay from the frequencies listed in Table 3.

The first and simpler method is use of a linear, least squares fit to the higher order harmonic frequencies. We assume that the cable is a taut string, and calculate the tension accordingly. A more complicated technique involves a non-linear fit using Equation 3, which describes the relationship between the actual stay frequencies and the equivalent taut string frequencies.

Using the linear fit taut string method, we calculate a fundamental frequency of 3.043 Hz and a stay tension of 406 kips. For the non-linear technique, we get a fundamental frequency of 3.033 Hz and a tension of 404 kips. Both of these results compare favorably with the design tension of 414 kips. The results along with the associated percentage deviations are tabulated in Table 4.

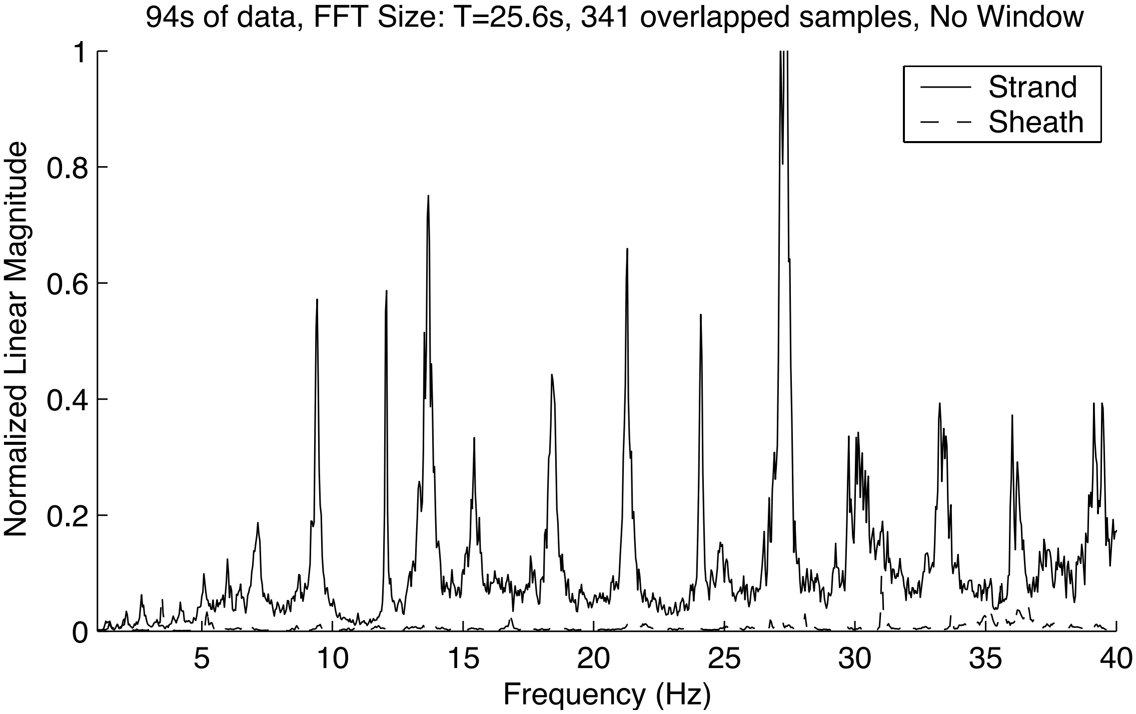

Figure 5: Spectra of an individual strand, and that of a completed stay

Table 3: Harmonic frequencies obtained from experimental vibration data

Harmonic Number	3	4	5	6	7	8	9
Measured Frequency (Hz)	9.41	12.07	15.43	18.40	21.29	24.10	27.34

Table 4: Stay Properties based upon spectral analysis

	Fundamental Frequency (Hz)	Stay Tension (kips)	Deviation from Design tension
Linear Fit	3.043	406	1.9%
Non-Linear Fit	3.033	404	2.4%

FUTURE DIRECTIONS

At the present time, we are still developing experimental practices based upon the use of our reference data acquisition system, the VXITech 1432a. The VXI system is well established equipment with a proven track record, but it is not well suited to long term monitoring due to its high cost and relative fragility.

The requirements for long term stay monitoring are better suited to data loggers. The low frequencies mean that our sample rates are modest, although good spectral resolution requires that we take data over long intervals. A sampling rate of 100Hz gives us good results for frequencies up to about 40Hz. Based upon the sampling rate, we need approximately 750 kilobytes of storage per channel per hour. This is well within the capacities of modern data logging equipment, especially when combined with triggering events such as truck traffic or high winds that can reduce data collection to times when we are likely to observe stays in a high state of excitation.

With regards to data analysis, we are currently exploring different techniques for frequency extraction. Good techniques should be less subjective and more amenable to automation. Averaging and windowing techniques will be applied to the data to reduce experimental error and achieve results closer to those predicted by theory. We are currently exploring analytical tools such as the taut string model, and Equation 3 in conjunction with the taut string model, to estimate the tension from the measured frequencies. The trade-off in choosing any one of these tools is between complexity and the significance of the error in the predicted tension.

Ultimately, we wish to use these data logger technologies to create an automated solution that collects and stores data without human intervention. The likely solution based upon what we have learned to date will involve the use of the Campbell Scientific CR-1000 data logger in conjunction with cellular modem technologies, feeding data into a web server for presentation of the data to the end user.

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