Invited Talk

Review of Acoustic Emission Source Mechanisms on Large Movable Structures

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ABSTRACT: This paper reviews and compares three case studies involving acoustic emission (AE) monitoring of anomalous noises on large movement structures. In particular, probable source mechanisms for the various audible noises observed on the structure and investigated by AE and other measurements are identified and discussed. The three case studies include a movable stadium roof and two movable bridges, one bascule-type and one swing-type. The stadium roof and bascule bridge both showed AE correlated with similar stick-slip behaviors, albeit on two very different mechanisms. The swing bridge showed two distinct noise sources, each associated with different aspects of bridge motion.

15.1 INTRODUCTION

In the course of operation, movable structures such as stadium roofs, movable bridges, and industrial gantries sometimes emit audible noises loud enough to be disturbing the structure owner and the public. This paper will review three cases studies in which such loud noises, termed anomalous audible events (AAEs), were observed during commissioning of movable structures, with particular consideration of probable underlying noise source mechanisms. In each case, the structure owner needed to know whether the noises were benign or indicative of some mechanical (i.e. with the lift machinery) or structural problem. Identification of AAE source locations on large steel structures is challenging due to sound propagation and re-radiation through structural members, giving the impression to the human ear that the sound is coming from all around. It has been shown [e.g. 1,2] that acoustic emission (AE) monitoring with judicious sensor placement on the structural steel can provide unambiguous AAE source location results. Consideration of source location results along with structural/mechanical measurements such as strain, displacement, and rotation can provide insight into the underlying source mechanism, which in turn informs decision-making by the structure owner.

1.1.1 Overview of Case Studies

Three case studies are considered herein. All of these structures are located in the northern tier of the United States, in climates with hot summers and cold winters. Deicing salts are used on both bridges. The structures are:

1) Movable roof on a baseball stadium
2) Rolling bascule bridge carrying a town street over a freshwater commercial waterway
3) Swing bridge carrying a city arterial street over a marine commercial waterway

1.1.2 Considerations for Movable Structures

Movable structures present a variety of engineering challenge not found in static structures. Considerable wear occurs on bearing surfaces, and members are often subject to large cyclic loads, up to complete stress reversals [3]. In this sense, movable bridges and stadium roofs behave more like large machines than structures. For example, the primary girders on a bascule-type movable bridge change conceptually from a simple span when the bridge is closed and locked, to a cantilever span when the bridge first opens, to something like a beam-column with both bending and axial loads when the bridge is fully open (i.e., the leaf is nearly vertical). Access to structural and mechanical elements of interest also presents challenges. For example, bearings or raceways in a swing-type structure may be located in a confined space, as in the swing bridge case study. In addition, the size of the structure and the relative motion between various structural elements complicates sensor installation and cable connections to the AE measurement equipment – it is typically necessary to adopt a piecewise approach to instrumentation. Finally, a considerable amount of spurious noise (i.e. other than AAEs) is generated during normal operation from benign processes such as sliding movements on bearings, crushing of oxides and debris on rolling surfaces, and so forth. These noises must be filtered away to concentrate on AAEs.

15.2 CASE STUDY: STADIUM ROOF

AE monitoring was used to identify AAE sources on the radial retractable roof at the Miller Park baseball stadium in Milwaukee, Wisconsin, USA shortly after the structure opened to the public. The radial roof opens and closes like a handheld folding fan, as shown in Figure 1. This roof system is both a signature aesthetic feature of the structure and an essential operating mechanism – unlike most domed stadiums, Miller Park includes a grass (rather than artificial turf) field requiring regular doses of sunlight through the opened roof.

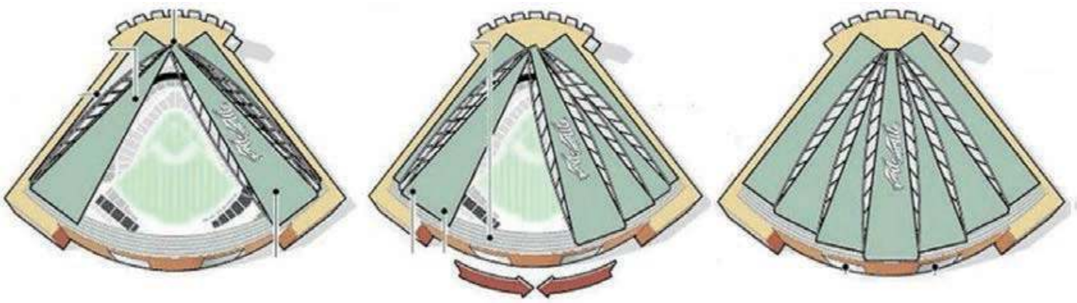

Figure 1: Stadium roof closing sequence showing roof panels pivoting on bearings above home plate (*Milwaukee Journal-Sentinel* illustration)

Each of the five movable roof panels is supported by a bearing on a tree-like structure behind home plate. The tree structure and a typical bearing are shown in annotated photographs in Figure 2. Each panel weighs between 1,590 and 2,270 metric tons (3.5-5.0 million pounds), with approximately 40% of the load supported by the pivot bearings [4]. The remainder of the load is supported by motorized bogies on the outfield wall, which also provide the tractive effort to move the panels along a railroad-style track. The movable roof panels span approximately 180 m (600 ft) from the pivot bearings to the track [5].

(a) (b)

Figure 2: (a) Annotated photograph showing one side of tree-like structure supporting the five roof panel pivot bearings; (b) close-up of typical roof panel bearing showing location of AE transducer

Instrumentation and monitoring of the roof panels was described by Prine [2]. Each of the five pivot bearings was instrumented in turn and tested by moving the corresponding roof panel. A non-contact laser displacement sensor measured the position of the roof panel truss as the truss pivoted about the bearing. The laser displacement sensor had micrometer sensitivity but limited range - approximately 6 mm. Thus, displacement data were available for only the first 6 mm of travel. Nevertheless, plots of acoustic emission peak amplitude and roof truss rotation revealed correlation between AAEs and changes in the time rate of displacement, as shown in Figure 3.

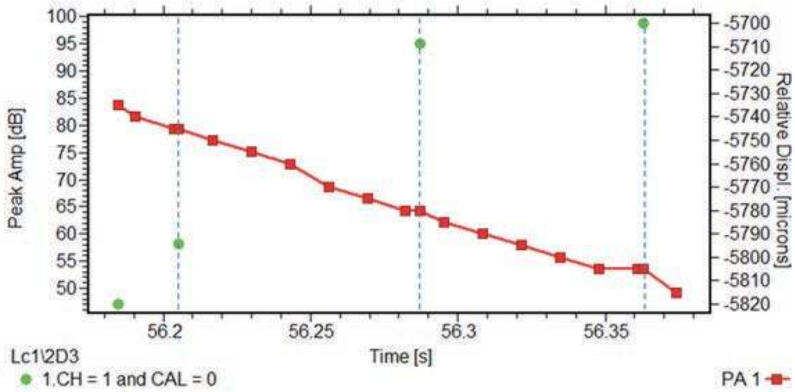

Figure 3: Time history of AE amplitude (green dots) and roof panel truss displacement (red line) showing correlation between AE and changes in displacement rate. Dashed lines indicate times of AE events, for comparison to displacement data.

It is clear from Figure 3 that acoustic emission hits are correlated with momentary pauses in change in displacement followed by resumption of movement – that is, stick-slip behavior. Due to the long span of the roof panel trusses, very small displacements/rotations at the bearing correspond to large movements at the drive bogies along the outfield wall. When the home plate bearing sticks, considerable strain energy may accumulate in the roof truss until the bearing slips. This undesirable behavior indicated that the selected bearing design was not suitable to the application. When the bearings were replaced with thrust bearings designed to accommodate the downward load associated with the weight of the roof panels, the AAEs ceased [5]. The stadium roof remains in service and is operated frequently during baseball season.

15.3 CASE STUDY: ROLLING BASCULE BRIDGE

AE monitoring was used to characterize audible noises generated during opening and closing of a Scherzer-type rolling bascule bridge over a busy waterway. Rolling bascule bridges open by rocking along a toothed track plate at the heel of the bascule girder, as shown in elevation view sketch and photograph in Figure 4. During operation, as well as when the bridge is locked in the closed position, the entire weight of the movable leaf (approximately 450 metric tons) is supported by a relatively small contact area on the lower track plate. This contact area moves along the upper and lower track plates during bridge movement.

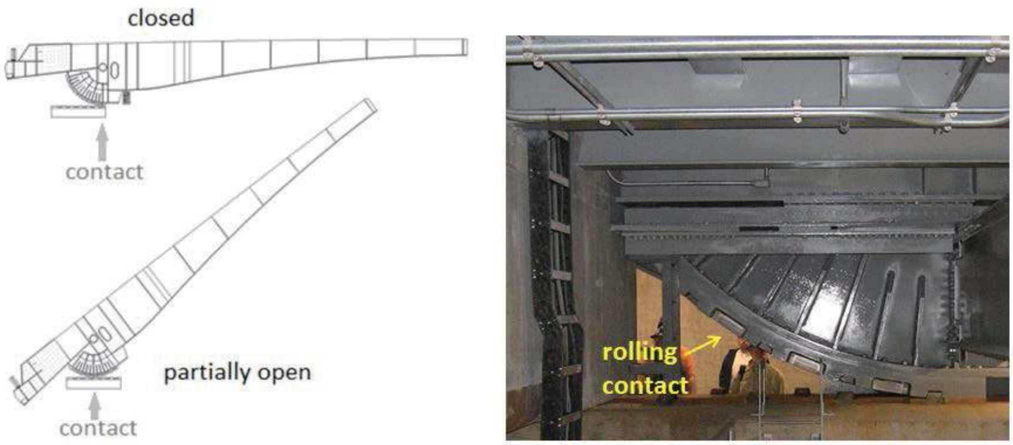

Figure 4: Sketch of bascule bridge leaf and photograph of bascule girder heel showing moving contact areas

Instrumentation and data reduction (including development of post-processing filters) for the rolling bascule bridge is described in a previous paper [2]. After the drive machinery had been ruled out by first-hit analysis, linear and planar location analyses were employed to determine whether AAEs corresponded to particular contact locations during lift cycles. Linear location analysis along the top and bottom track plates showed that AE events associated with AAEs followed the rolling contact point between those plates. Planar analysis, in which an array of AE transducers was deployed to cover a wide area of the heel of the bascule girder, yielded unambiguous results indicating that AE events associated with AAEs occurred exclusively along the bottom edge of the bascule girder heel, as shown in Figure 5.

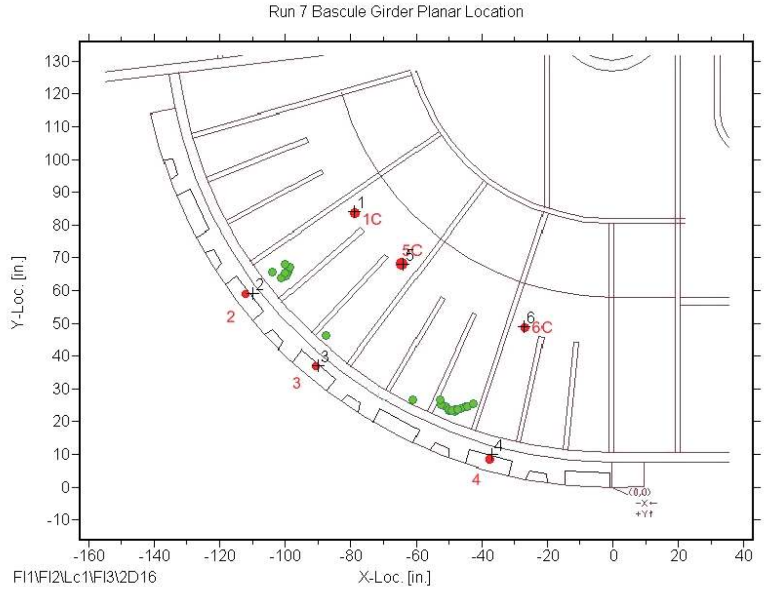

Figure 5: Planar location results showing events along bottom flange of bascule girder heel. AE transducer locations are indicated by the numbered red dots, and located AE events by green dots.

While the source location of the AAEs was evident from the planar location results, the specific source mechanism remained unclear. A toothed track plate is bolted to the bottom flange of the bascule girder. This curved upper track plate mates with the flat lower track plate as the bridge moves. The bolted connections consist of groups of bolts on the bottom flange (on either side of the bascule girder web; each group of bolts was separated from the groups on either side by a radial stiffener. These long and short radial stiffeners are visible in the drawing in Figure 5.

After the bolts themselves were eliminated as potential AE sources by a close-up transducer array, it was hypothesized that the AAEs may originate elsewhere along the bascule girder-upper track plate interface. An orthogonal pair of eddy-current type non-contact displacement sensors was deployed to measure any displacement or deformation along or perpendicular to the interface – in other words, quasi-shear or normal deformation. A nearby tilt sensor nearby measured the angle of the bridge, from which the track plate contact position could be calculated. These sensor locations and orientations are shown in Figure 6.

The measured displacements – particularly the quasi-shear displacements – presented a distinct stepwise pattern during portions of the bridge lift cycle. Timestamps of acoustic emission events associated with AAEs are superimposed on the quasi-shear displacement time histories in Figure 7. While the total change in displacement during the lift cycle is quite small (64 mm or 0.025 inch), it is evident, particularly in Figure 7b, that AAEs are correlated almost one-to-one with stepwise jumps in displacement.

Because the apparent stick-slip movements were very small and occurred away from the bolts, the bridge designer judged the AAEs and the underlying stick-slip mechanism to be benign. Anecdotal reports indicated that the AAEs subsided during the first year of regular operation of the bridge. These reports suggest that the stick-slip action on the bascule girder-track plate interface was related to “break-in” initial wear on the interface. The bridge remains in regular operation, opening tens of times daily during the summer months.

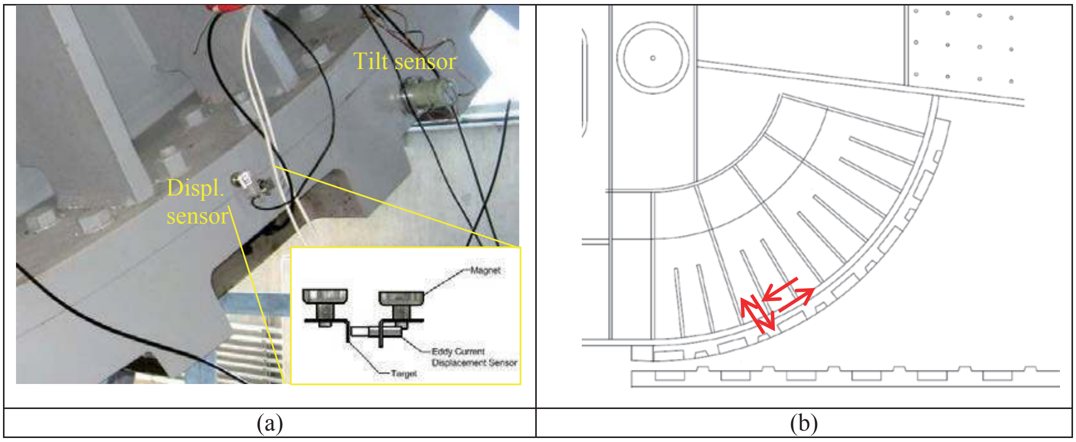

Figure 6: Photograph and sketch showing displacement sensor (a) location and (b) orientation (exaggerated scale) on bascule girder - upper track plate interface

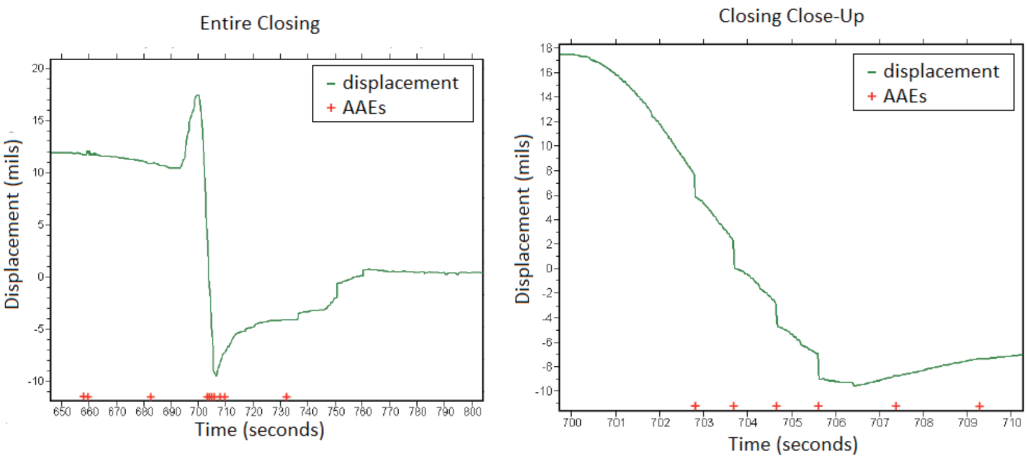

Figure 7: Correlation of AAEs with displacement along the interface between the bascule girder bottom flange and the curved upper track plate during bridge closing, showing (a) entire closing and (b) close-up of 10 second period of greatest movement

15.4 CASE STUDY: SWING BRIDGE

Anomalous audible events of two distinct types – one described as “clicking”, the other as “popping” or “booming” – were reported during operation of a swing bridge carrying a city arterial street across a busy marine waterway. AE monitoring was employed to characterize the two types of AAEs. The bridge owner was particularly curious whether AAEs were associated with any particular bridge position or rotational speed.

Instrumentation and data reduction (including development of post-processing filters) for the swing bridge is described in a previous paper [2]. Following preliminary tests to rule out other areas of the bridge, the center pivot and outer drive pinion areas were identified as likely noise sources. Locations on the center pivot area of the bridge are described using the clock face system shown in Figure 8a. In this scheme, the 9 o’clock-3 o’clock axis represents the longitudinal axis of the bridge when closed, and the 12 o’clock-6 o’clock axis represents the bridge’s fully open position. A rotary encoder on the center gear recorded bridge position.

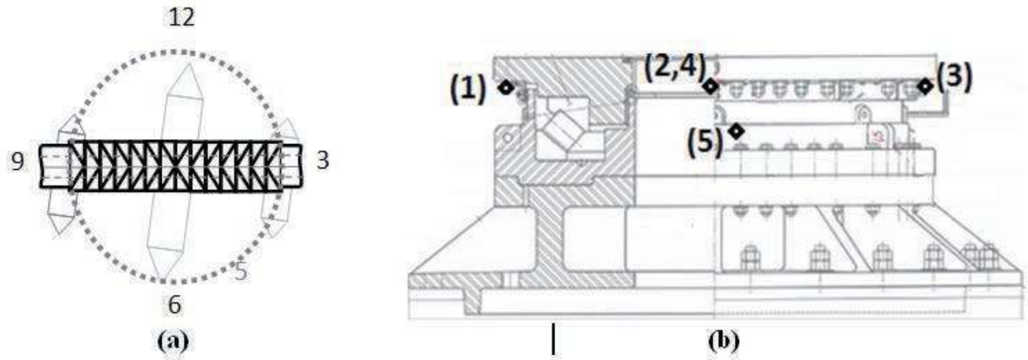

Figure 8: (a) Plan view of swing bridge with clock face representation of bridge angle superimposed; (b) Elevation view of sketch of AE transducer layout on pivot

Testing revealed that clicking-type AAEs occurred only while the bridge was in motion. When the bridge was moving at approximately constant speed, AAEs occurred at regular five second intervals and were not generally associated with bridge starts or stops. It was hypothesized that a particular "hot spot" along the rotation arc might be the source of the periodic clicking AAEs. Planar location analysis was conducted on the plate at the top of the pivot bearing (AE channels 1-4 in Figure 8b) to test the hot spot hypothesis. The results, shown in Figure 9, were consistent with an AAE hot spot at the 5 o'clock position.

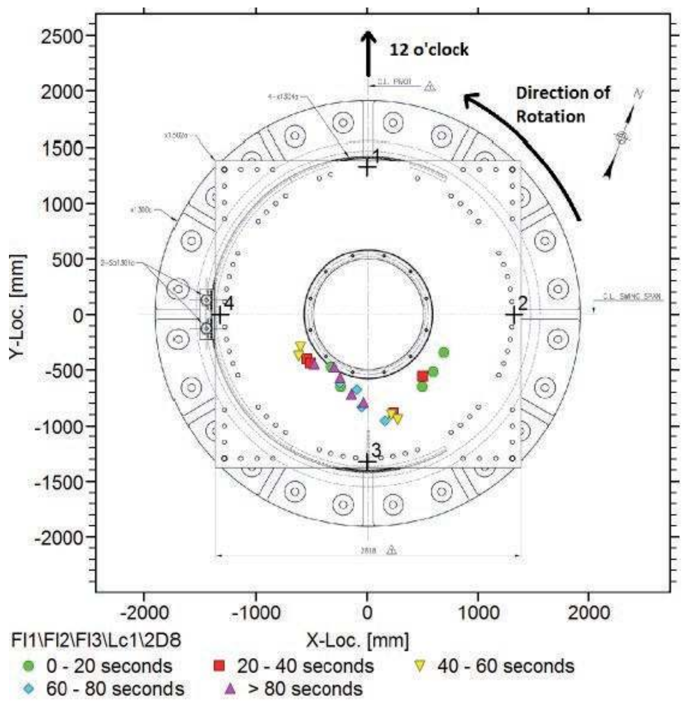

Figure 9: Arc of located events (divided into 20-second time bins) in pivot area during rotation of swing bridge

Specifically, when locatable events are distributed into bins based upon the time within the bridge movement at which they occurred, it is evident that earlier AAEs tend to occur toward the 5 o'clock position, and the subsequent AAEs generally tend to occur clockwise of that position, subtending an arc from 5 o'clock to 8 o'clock. This distribution is generally consistent with the motion of the bridge as it moves from fully closed to fully open; thus it may be reasonably concluded that a single source at the 5 o'clock position on the pivot base could cause the clicking-type AAEs.

The “popping” or “booming”-type AAEs on the swing bridge were found to be fundamentally different than the clicking type. While the clicks were strongly periodic and associated with steady motion, the booms occurred almost exclusively during stops and starts, as shown in the distribution of AAEs by bridge angle in Figure 10.

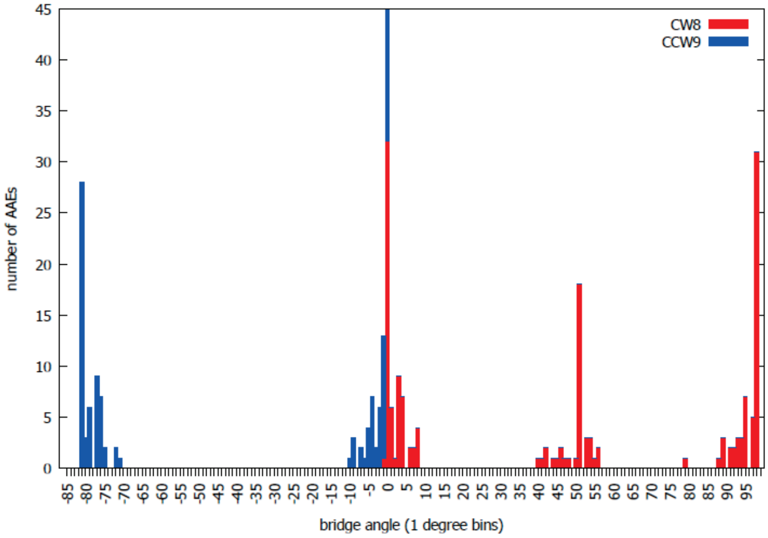

Figure 10: Stacked histogram of AAEs (n = 257) with bridge angle for selected clockwise (red) and counterclockwise (blue) bridge movements, showing clusters of AAEs at starts and stops, including a pause at +52 degrees during clockwise motion. Figure courtesy of Daniel Marron (unpublished data).

Linear and planar location analyses showed that the booms originated along the box girders supporting the drive pinions. The drive pinions (with drive shafts oriented vertically) engage a rack on a large-diameter ring about the center pivot point. Locatable events were concentrated near the groups of bolts that tie the pinion bearings (supporting the vertical pinion shafts) to the box girder, as illustrated by the annotated histogram in Figure 11.

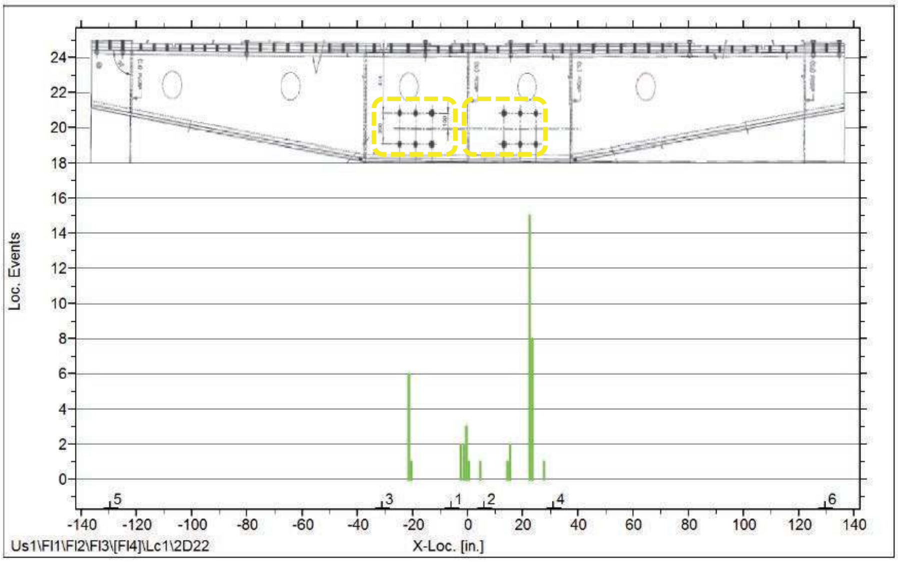

Figure 11: Distribution of AAE source locations along pinion girder. Pinion bearing/box girder through-bolt groups are highlighted in yellow. Figure courtesy of Daniel Marron (unpublished data).

15.5 DISCUSSION AND CONCLUSIONS

The three case studies demonstrate that AE may be successfully applied to localization and characterization of anomalous acoustic events on large movable structures, and that the AE method can identify events with various underlying acoustic source mechanisms. AAEs may be produced by movable structures in several ways. Despite differences in structure purpose and geometry, similar micro-level source mechanisms are present. In the case of the swing bridge, two distinct source mechanisms were identified, each with particular relationships to bridge motion (i.e. constant speed vs start/stop).

1.1.3 Stick-Slip Behavior

The baseball stadium roof and the rolling bascule bridge present clear examples of stick-slip behavior leading to AAEs. Displacement during the slip was quite small, on the order of micrometers; however, the slip occurred nearly instantaneously, resulting in a sudden energy release. Typically, processes producing audible sounds (e.g. AAEs) emit acoustic energy over very broad frequency spectrum [6,7]; thus it is expected that the AAEs would be readily detectable by both the human ear (sensitive from roughly 20 Hz to 20 kHz) and commercially-available AE transducers (sensitive from roughly 150 kHz to 675 kHz).

Both structures emitted AAEs throughout movement cycles, as opposed to emission during start/stop acceleration only. In both cases, stick-slip behavior is almost certainly related to the high normal forces on the surface. On the stadium roof, approximately half the weight of the roof panel acted normally to the bearing surfaces; on the bascule bridge, it is believed that the vertical stiffeners played a role in "focusing" loads to particular areas.

1.1.4 Localized Movement Around Bolts

The "popping" AAEs observed on the swing bridge appear to be related to localized movement around the bolts in the pinion girder. However, similar tests to monitor bolted connections between the track place and bascule girder on the rolling bascule bridge yielded no significant acoustic emissions. The difference between these two observations is likely related to the stiffness of the thick bascule girder flange versus the relatively thin walls of the swing bridge pinion box girder. Close-in displacement measurements showed that the pinion box girder does deflect during starts and stops, indicating a possible "oil can" deflection mode at moments of high stress from the pinion torque during movement starts and stops. Thus it seems that in areas of relatively lower stiffness, localized movement around bolts can be a source of AAEs.

1.1.5 "Hot Spots"

Both bridges showed "hot spots", areas of concentrated AE activity associated with AAEs. On the bascule bridge, planar location analysis showed that most AE events occurred along a line (i.e., the interface between the bascule girder heel and the curved upper track plate). On the swing bridge, the "clicking" AAEs were shown to originate from the center pivot area; planar location vs. time analysis suggests that the AAEs may be associated with a particular point on the center pivot bearing. It is by no means surprising that acoustic emission phenomena would be concentrated in particular high-stress regions

1.1.6 Limitations and Opportunities

Uniqueness of large civil structures, as opposed to manufactured systems, presents some challenges for scientific analysis of acoustic emission behavior associated with AAEs. Each structure in the case studies was designed for and constructed at a specific location. Even if similar structures were available for comparison testing, site-specific design elements, site conditions, construction details, and operating practices affect the boundary conditions for the structure itself as well as the dynamic processes associated with movements. This uniqueness of constructed facilities stands in contrast to the repeatability found in manufactured systems, which are built in large volumes under controlled conditions. Furthermore, the scope of investigations for movable structures is limited by access methods and time available for testing. Since structures are typically closed to the public during testing, structure owners are motivated to conclude testing as soon as actionable information is obtained, rather than conduct additional work to fully characterize the problem. Thus, opportunities for detailed in-situ investigation of the mechanics underlying AAE phenomena are limited. It is hoped that building a library of case studies in the literature will provide sufficient information to inform faithful simulations and laboratory investigations. In addition, guidance from movable structure case studies may help forge additional connections laboratory-scale phenomena in the existing AE literature and the experiences of full-scale field observations.

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