Noise Localization via Acoustic Emission Monitoring on a Rolling Bascule Bridge

DAVID E. KOSNIK, DANIEL R. MARRON, DAVID J. CORR, and MATHEW P. KOTOWSKY, Northwestern University, Evanston, Illinois

IBC-10-68

KEYWORDS: acoustic emission, rolling bascule bridge, noise localization

ABSTRACT:

Acoustic emission monitoring was used to locate the source of loud noises generated during operation of a bascule bridge over a busy waterway. Initial analyses ruled out the machinery as the noise source and showed that the noises were coming from the heel area of the bascule girder. Source location analysis suggested that the bangs were generated along the bascule girder-track plate interface. It is hypothesized that highly localized stick-slip behavior is the cause.

INTRODUCTION

Lift bridges and other large movable structures present special engineering challenges. In many ways, they more closely resemble machines than structures: much movement (and therefore wear) may occur on bearing surfaces, and members are subject to large cyclic loads, sometimes including complete stress reversals [1]. While few new movable bridges are being built, and many movable bridges are slated for replacement by high fixed bridges, those that do exist are often important links in the communities they serve. In many cases, proper operation of a movable bridge is critical to the flow of both highway (or railroad) and marine traffic.

NOISE LOCALIZATION Occasionally, movable structures have been observed to emit audible noises loud enough to be disturbing to people. These noises may be benign or indications of structural or machinery problems — additional investigation is required to determine if the noises are cause for concern.

Audible noises in large steel structures are extremely difficult to localize by ear. This is because steel provides an excellent path for sound. Steel can carry and re-radiate sound over great distances. Furthermore, because the velocity of sound in steel is over 17 times faster than in air, re-radiated sound from the steel can appear to originate from multiple sources.

Acoustic emission monitoring provides a useful method for locating noise sources in steel structures. Processes that produce audible sounds, such as stick-slip behavior or fretting of bolted connections, typically produce acoustic energy in a very broad frequency spectrum [2, 3]. By using AE transducers with resonant frequencies in the 150–650 kHz band, the higher-frequency signals traveling from the audible event through the steel are captured. These frequencies attenuate quickly in air, so re-radiated sound does not complicate source location. Therefore, an array of 150–650 kHz resonant sensors coupled directly to the structure can accurately determine the location of the source by standard AE location techniques based on time-of-arrival measurement, a standard technique for AE source location [4]. This approach eliminates the confusing airborne low-frequency (i.e., audible) sound and generally produces unambiguous source location.

AE source location generally is based upon the assumption that transducers are located in an infinite line or plane where stress waves propagate at the same velocity in all directions [4]. By and large, these assumptions are reasonable for large steel structures, since steel — at least at the macro scale — is a fairly homogeneous, isotropic material.

This general time of arrival technique is known as first hit analysis. When a discrete physical process, such as stick-slip, produces acoustic energy, it propagates outward as sound waves along all available paths in the structure. Each discrete physical process generating bursts of acoustic energy corresponds to the AE term event. When sound waves from an event reach an AE transducer and its amplitude is above the recording
threshold, it is termed a hit and the AE monitor records information about that sound wave for a set period of time. This means that on our six channel monitor, one event can cause from one to six hits to be logged for a single event. We can determine which sensor is the first hit based on time of arrival. Logically, the source of the sound will be closest to the sensor with a first hit for that event. Our choice of sensor layout combined with the geometry of the structure and the average of first hits per lift cycle at each sensor can be used to determine the location of the acoustic source.

THE ROLLING LEAF BASCULE BRIDGE
Acoustic emission monitoring was used to locate the source of audible "banging" noises generated during opening and closing of a large Scherzer-type rolling bascule bridge over a busy waterway. An overall photograph of the bridge is shown in Figure 1.

Figure 1 - Overall photograph of the bridge
Observations indicated that the bangs seemed to occur almost exclusively on the south bascule girder of the west leaf of the bridge. AE testing was undertaken to determine the bangs’ source location and provide insight into the source mechanisms. Figure 3 is an elevation view of the west leaf showing the bascule girder and the track plate upon which it rolls as the bridge opens.

EQUIPMENT AND METHODS
All acoustic emission tests performed during this study were made using a six-channel Vallen Systeme AMSY-5 monitor and VS375-RIC 375 kHz-resonant piezoelectric transducers with integral preamplifiers. The transducers were acoustically coupled to the structure with high vacuum silicone grease. Because the AE amplitude of the bangs was expected to be high, the bridge paint was left intact to provide some attenuation. Likewise, 375 kHz-resonant transducers were selected because they are less sensitive overall than more typical 150 kHz-resonant transducers. The AMSY-5 was configured with a recording threshold of 50.1 dB and a gain setting of 34 dB on the integrated preamplifiers.

On some of the test runs, two Kaman Instrumentation KD-2300 1SU eddy-current displacement sensors and two Schaevitz Accustar II electronic tiltmeters were affixed to the bridge and connected to the AE monitor’s parametric inputs to provide additional information. A digital video camera was used to record all tests.

FILTERING The initial tests showed an extremely high level of acoustic activity. There were thousands of locatable events, hundreds of which had amplitudes of 99 dB, indicating saturation of the AE monitor. Since the primary goal was to locate the source of the noises, saturation did not pose a problem — only time-of-arrival differences from transducers in an array of known geometry are needed for location. Nonetheless, several thousand AE events were detected in each run; given that there were at most a few dozen audible bangs per run, it was hypothesized that only a small subset of saturated 99 dB-amplitude AE events corresponded to the bangs detected by human ears.
Extensive post-processing was necessary to extract only the AE events corresponding to audible bangs. The digital video (DV) recordings of each run provided a convenient starting point. The DV tapes were transferred to a computer for processing and edited into discrete files corresponding to each test run. The audio track was then extracted to wav-format digital sound files and edited with open-source graphical video [5] and audio editing [6] applications to obtain the time index of each bang. Synchronization between timestamps in the DV audio track and AE data file was achieved by matching the calibration pulses from the AE files with the audible chirps produced by the AE equipment during calibration, as recorded by the DV camera. The bangs were easily distinguished from background noise in the audio track, both by ear and by visual examination of the audio waveform. However, this qualitative distinction itself would have been impractical for extracting the AE data corresponding to the many audible bangs — a filter in terms of common waveform parameters, such as amplitude or energy, had to be developed.

Peak amplitude was useless for discriminating audible bangs from other noises since many hits saturated the transducer, causing the AE monitor to report a peak amplitude of 99 dB, whether the true amplitude was 99.1 dB or 200 dB, for example. Event energy, however, remains a useful indicator even when the sensor is saturated and the waveform is “clipped” at the voltage equivalent to 99 dB because it is related to the area under the absolute value voltage versus time curve from the sensor. As such, it provides an indication of relative strength of an event because it quantifies the amount of time required for the event to “ring down.” Discriminating on the basis of the number of counts per event — that is, the ring-down count, another common AE parameter — would have produced similar results.

Thus, event energy was selected as the most useful descriptor. Strictly speaking, event energy is related to the area under the transient voltage-squared versus time curve. That is, the true event energy [7] is proportional to the electrical energy $U$ of an AE event, given by Eq. (1):

$$U = \frac{1}{R} \int |V(t)|^2 dt$$  \hspace{1cm} (1)

where $V(t)$ is the time-varying voltage signal from the transducer and $R$ is the electrical resistance of the measurement equipment. However, real-time calculation of this quantity requires a squarer chip in the AE hardware. Where a squarer chip is not available (as in this study), event energy or “signal strength” is alternatively defined in Eq. (2):

$$U = \frac{1}{R} \int |V(t)| dt$$  \hspace{1cm} (2)

In this case, the terms “signal strength” and “event energy” are used interchangeably, and energy units are no longer physical energy (i.e., joules). Rather, energy units are redefined [8] as:

$$1 \text{ eu} = (1 \times 10^{-9}) V \times s$$  \hspace{1cm} (3)

While the units of Eqs. (2) and (3) are not true energy in the physical sense, the relationship is sufficient to distinguish high- from low-energy events in steel structures, particularly when peak amplitude is not a useful descriptor due to sensor saturation. The minimum energy corresponding to audible bangs was determined empirically by examining the parameters of AE hits that occurred at the same time as audible bangs identified from the DV audio track. After several iterations, 600,000 AE energy units was found to be an acceptable criterion; this value represents roughly the most energetic 1% of events. The correspondence of events with energy greater than 600,000 eu to audible bangs on the audio track was nearly one-to-one. Figure 4 shows this relationship.

![Figure 4 - Validation of energy filter used to identify audible bangs.](image)

**TESTING PROCEDURE**

Acoustic emission tests were conducted during ten complete lift cycles using four different array geometries. Two of the ten runs were performed on the quiet east leaf as a control. The primary goal was to determine the physical location of the source of the audible bangs emitted during bridge movement. Based on initial data and conversations with the design engineers, the number and foci of the tests were expanded to address specific concerns such as displacement of the curved track plate and correlation of AE events with bridge position. On some runs, bascule girder tilt (which can be directly related to linear position along the track plate) and sub-mil resolution displacement data were taken to provide insight into the mechanism producing the bangs.

A rectangular coordinate system was defined with the origin at the point of contact between the bascule girder
and bottom track plate when the leaf is fully closed. For consistency with the standard Cartesian system, the bascule girder translates in the negative direction along the $x$-axis as the leaf opens. Figure 5 shows an overview of the bascule girder/track area with the primary sensor locations and coordinate system.

![Figure 5 - Overview of bascule girder/track area showing primary sensor locations. Locations 2A and 4B were used only for displacement measurements described later.](image)

**INITIAL FIRST-HIT CHANNEL ANALYSIS**

The initial AE tests were first-hit analyses using the array shown in Figure 5. One AE transducer was placed near the pinion gear, three on the curved upper track plate, and two on the flat lower track plate. By determining which transducer is hit first by each AE event, it is possible to gain a rough idea of the location of AE sources. First-hit analysis was therefore useful to answer the question of whether the bangs were originating in the machinery room and to inform transducer placement for subsequent tests.

Analysis showed that 90% of high-energy AE events hit Channels 2, 3, or 4 first, indicating that they originated near the curved track plate-bascule girder interface. The balance originate near the pinion shaft; few high-energy AE events originate from the flat track plate. Thus, the source of the bangs was not the machinery room, as that would have produced many first hits near the pinion. Neither was the source along the flat bottom plate. The high AE activity on Channels 2–4 and the low to zero activity on the other regions made it clear that the region along the bascule girder heel and curved upper track plate was the likely source of the bangs.

**BASCULE GIRDER “UNROLLED” LINEAR LOCATION**

Acoustic emission monitoring can be used to locate acoustic sources in one, two, or three dimensions based upon time-of-arrival differences for an AE event which reaches sensors in an array of known geometry. For this test, one-dimensional location analysis was performed by “unrolling” the curved upper track plate on the bascule girder and treating it as a straight rod. The array geometry is shown in Figure 6. The corresponding coordinate system used for linear location along the curved upper track plate is shown in Figure 7.

![Figure 6 - AE array for “unrolled” linear location and planar location analyses.](image)

AE source locations were calculated by Vallen VisualAE software [9] using linear location source location based on time-of-arrival differences [4]. Sensors 1C, 5C, and 6C were employed as guard transducers to intercept noise originating elsewhere on the structure; any events that hit one of the guard channels first were rejected. A tilt sensor on the bascule girder measured the angle of the girder during the opening and closing. This angle was used to calculate the linear position of the point of contact along the track plate at a given time.

Figure 8 shows the location of AE hits along the “unrolled” upper track plate along with the position of the contact area as the bridge opens and closes. In general, the source locations of the hits along the curved upper track plate follow the location of the contact area during the lift cycle. When the contact position is outside the AE transducer array ($x < -128\text{ in};$ time $t$ between 425 and 675 seconds), the source locations cease to follow the contact position and instead remain at about the same $x$ location as Sensor 2. This was interpreted to be a consequence of the source location algorithm’s tendency to fail when the source is outside the geometry of the AE transducer array; thus, it is reasonable to extrapolate that the source locations likely did continue to follow the contact position for positions $x < -128$ in and times between
425 sec and 675 sec. Comparison of the filtered and unfiltered data in Figures 8a and 8b illustrates the importance of the high-energy filter in providing clear location of audible bangs among the many low-energy emissions along the contact surface.

**Figure 8** - Linear location of (a) all events and (b) high-energy events only along the upper track plate during opening and closing of the west leaf

**PLANAR LOCATION ANALYSIS**

Two-dimensional source locations were calculated using time-of-arrival differences from the transducer array shown in Figure 6. For planar location, Sensors 1, 5, and 6 were used in combined guard/normal mode; that is, AE events that reached those sensors first were rejected outright, eliminating noise from the pinion, while events that reached those channels after reaching Channels 2, 3, or 4 were located using the time-of-arrival data from all channels.

The planar location results, shown in Figure 9, indicate that the bulk of the locatable events originate along the arc of the bascule girder and curved upper track plate. Again, comparison of unfiltered and filtered data in Figures 9a and 9b, respectively, illustrates the importance of the energy filter in extracting useful information from the abundance of AE data. While the precision of the planar location results was reduced due to the complicated geometry of the bascule girder/curved track plate interface, the location results seem to strongly support the hypothesis that the bangs originate somewhere along the bottom arc of the bascule girder.

**MICRO-LOCATION AROUND BOLTS**

A separate AE test run was performed specifically to determine if the bolts connecting the bascule girder to the curved track plate were the source of the audible bangs. Transducers were placed inside the set of bolts on the bottom flange of the bascule girder in a selected “bay” between two radial stiffeners — one full-length and one short stiffener. Guard transducers were installed on the bascule girder bottom flange outside the bay of interest to intercept noise. No high-energy AE events (energy greater than 600,000 AE energy units) were recorded within the micro-location array. If the turned or tapped bolts were the source of the audible bangs, high-energy
AE events would almost certainly have been detected near the bolts themselves. While only one bay was tested in this manner, the complete absence of high-energy AE in the tested bay seems to rule out the bolts as the source of the audible bangs.

**DISPLACEMENT MEASUREMENTS**

Displacements along the interface between the bascule girder and curved track plate were measured to supplement the acoustic emission data. The displacement sensors were applied to various locations along the interface with a temporary magnetic-mount fixture, as shown in Figure 10.

Initially, displacement measurements were made in both parallel and perpendicular to the bascule girder-curved track plate interface — that is, in and normal to the plane of the bascule girder. The total ranges of motion parallel and perpendicular to the interface were approximately 32 mils (0.81 mm) and 7 mils (0.18 mm), respectively. Both showed a repeatable, quasi-static response to the position of the bascule girder. Since the parallel response was much greater than the perpendicular, only parallel measurements were made in subsequent tests. Figure 11 shows displacement along the gap at Location 4B with the position of contact between the bascule girder and track plate during a complete lift cycle. This displacement pattern is typical of all measured lift cycles: the behavior is repeatable and quasi-static, returning to zero at the end of the lift cycle.
APPARENT RELATION OF DISPLACEMENT AND AE

Displacements showed a rough correlation with high-energy AE events, as shown in Figures 12 and 13, wherein AE events can be seen near step-like jumps in the displacement record. The jumps are most pronounced when contact between the track plates is near the displacement sensor — which occurs around time = 700 seconds, as was shown in Figure 8. This suggests that the mechanism producing the bangs is related to the large, rapid changes in stress as the contact area moves. Based on the relationship between high energy AE and sharp jumps in displacement in Figures 12 and 13, it is hypothesized that the mechanism may be highly localized stick-slip behavior between the bascule girder and curved track plate.

Figure 12 - Run 7 parallel displacement at Location 4B during bridge opening with time indices corresponding to high-energy AE events indicated by crosses along the x-axis.

Figure 13 - Complete (a) and zoomed (b) plots of parallel displacement during bridge closing with time indices of high-energy AE events indicated by red crosses. Each jump in the displacement data is accompanied by high-energy AE.

CONCLUSIONS

Acoustic emission monitoring was carried out during ten lift cycles of a large rolling leaf bascule bridge to identify the source location of loud “bangs” that occurred during opening and closing, particularly on the west leaf. The recorded data were analyzed using several well-established techniques, including first-hit analysis, linear location analysis, and planar location analysis. The results strongly suggest that the source of the audible bangs is along the interface between the bascule girder and the curved track plate bolted to it.

First-hit analysis specifically ruled out the flat bottom track plate on which the bascule girder rolls as the source of the bangs: no high-energy AE events typical of the audible bangs were recorded along the bottom track plate. Likewise, very few high-energy AE events originated near the pinion drive shaft bearing area, eliminating that as the source of the audible bangs.

Planar micro-location analysis adjacent to the turned and tapped bolts connecting the bascule girder and curved upper track plate yielded no high-energy AE events. Thus, the bolts themselves are unlikely to be source of the bangs.
Linear and planar location analyses on the bascule girder and curved upper track plate showed that a large number of high-energy AE events originate near the bascule girder/curved track plate interface. Temporal comparison of the AE data with sub-mil resolution displacement data along the interface indicate a possible connection between AE events and local jumps in displacement data. This observation supports the hypothesis that the source of the bangs is highly localized stick-slip displacement along small patches along the interface.

This experience and others (e.g. Prine [10]) show that acoustic emission is a useful and practical technique for identifying the source of audible noises on movable structures. By coupling directly to steel and using AE transducers with resonant frequencies in the 150–375 kHz band, the problems of multiple acoustic paths and re-radiation are mitigated effectively. Once the source of the noises has been identified, investigation and engineering judgment can be focused on the subject detail.

**ACKNOWLEDGMENTS**

This work was funded by the Northwestern University Infrastructure Technology Institute, a National University Transportation Center supported by the US Department of Transportation Research and Innovative Technology Administration.

**REFERENCES**


