

MODAL ANALYSIS OF THE VENICE LAGOON INLETS AND THE EFFECT OF LONG WAVES RESONANCE ON THE Mo.S.E. SYSTEM BARRIER GATES

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The historic center of Venice has been increasingly exposed to flood events due to the well-known phenomenon of *acqua alta* (high water). The phenomenon is triggered by the superposition of tides, storm surges and the seiche waves of the water body in the Adriatic Sea. To reduce the hazards of flooding, four tidal barriers, namely the Mo.S.E. system, have been built, spanning the three inlets of the Venice Lagoon. The barriers consist of a series of 18 to 21 hollow steel gates that are unconnected to each other but hinged at the bottom, along a common axis on the seabed.

The design and the construction of the Mo.S.E. project, took more than forty years since its first ideation. One of the most significant challenges has been the modelling of the complex hydrodynamic behavior of the floating gates in waves and current. Specifically, two types of wave-forced oscillations affect the barriers. The first is related to the incoming short waves. These can induce not only a synchronous response, but also a subharmonic response with specific out of phase patterns, also subjected to modulational chaos (Mei et al 1994, Sammarco et al 1997a, b, Panizzo et al 2006). These modal oscillations were shown to be resonantly excited through a mechanism similar to the excitation of edge waves on a beach. The second type of oscillation is related to the incoming infragravity waves, generated by nonlinear effects as storm waves attack the coast. These long waves can be resonantly amplified into the lagoon inlets, which resemble in shape long and narrow bays. The effects on the tidal barriers can be significant, leading to large oscillations of the gates, mostly in phase.

Many scientific and technical investigations have been undertaken in the past by analytical, numerical and experimental means. Experimental set-up covered vertical and inclined gates in 2D wave flumes, in 3D wave tanks, and the whole four barriers and inlets in 3D layouts; scales ranged from 1:64 to 1:10.

Now that the Mo.S.E. system is operating, however, there finally exists the possibility of monitoring its actual prototype behavior under real waves attack. Since the first raising of the system, occurred in 2020, the time series of angles, waves, current and levels have been monitored in all the three inlets (see the companion abstract by Sammarco et al., 2023, which describes the dynamics of the gate barrier measured during the event of November 22nd, 2022). Preliminary analysis of the data shows both short and long waves induced gate oscillations. For example, Figure 1 reports the frequency spectra of gate 11 of San Nicolò barrier angular oscillations and of the wave spectra as recorded by an ADCP installed at the bottom of the inlet. It is noticeable the existence of large energy infragravity wave

components, able of triggering non negligible long period oscillations of the gates. Since the response of the gates, as for any dynamical system, is strongly dependent on the frequency of the forcing, it is of the utmost importance to predict what is the period of the long waves components that are likely to resonate in the inlets.

The resonant amplification of the long waves in the Venice lagoon inlet has been studied during the design activities of the Mo.S.E. system. In this paper a novel approach is used. It is based on the modal analysis technique introduced by Bellotti et al (2012b) and Bellotti (2020), on the basis of the work by Sobey (2006) and already successfully applied to study the resonance of tsunamis in coastal areas (Bellotti et al 2012a; Bellotti and Romano, 2017; Cortes et al 2017; Aranguiz et al 2019). The method can predict, independently from the forcing waves, the shape of the natural modes, their frequency and their amplification factor.

The model solves the classical homogeneous long waves equation in two horizontal directions:

$$\frac{\partial^2 \eta}{\partial t^2} - \nabla g h \nabla \eta = 0 \quad (1)$$

where η is the water free surface elevation, g the gravity acceleration, t is the time, h is the water depth. Reflective conditions are applied at the solid boundaries, while an approximate radiation condition is used at the offshore limit of the computational domain.

The Finite Element Method is used to convert Eq. (1) and the boundary conditions into a system of linear equations that reads as follows:

$$[M] \frac{d^2}{dt^2} \{\eta\} + [D] \frac{d}{dt} \{\eta\} + [K] \{\eta\} = 0 \quad (2)$$

Where M , D and K are the mass, damping and stiffness matrix, while $\{\eta\}$ is the time-varying vector of the surface elevation at each computational point.

A change of basis is used to develop the modal solver. The vector $\{\eta\}$ is then expressed as $\{\eta\} = \{V\} T_0 e^{\lambda t}$, where the vector $\{V\}$ does not change with time.

By substituting the proposed expression for the solution into the system of linear equations it results:

$$([M] \cdot \lambda^2 + [D] \cdot \lambda + [K]) \{V\} = 0 \quad (3)$$

This is a polynomial eigenvalue problem that admits a number of eigenvalues (λ) and eigenvectors ($\{V\}$) equal to the number of degrees of freedom of the system, plus the corresponding complex conjugates. The problem is solved in MATLAB using the function *polyeig*. The eigenvectors and the eigenvalues take complex values,

as the eigensolution does also represent partially progressing waves, radiating through the open boundary. The imaginary part of each eigenvalue represents the angular frequency of the mode, while the real part represents an exponential damping factor in time. A careful analysis of the results will be carried out in order to extract the eigensolutions that represent actual long waves resonating into the inlets, while discarding those solutions of negligible practical interest. Figure 2 reports a sample computational FEM grid related to the Chioggia inlet, while in the Figure 3 the surface elevation pertaining to the first lowest frequency mode and the mode that induces large elevation in the navigation lock are plotted as color contours.

The results of the study will be compared with the resonant frequencies estimated by the actual measured wave and gate oscillation spectra, as the sample of Figure 1. An in-depth modal analysis for the three inlets is ongoing and detailed results will be shown at the Conference. It is expected that the analysis will shed some lights on the complex wave-gate interaction processes, that for many years have kept busy scientists and engineers involved in the design of the Mo.S.E. system.



Figure 1 - Gate oscillation (black) and wave motion (red) spectra for Gate 11 of San Nicolò barrier.

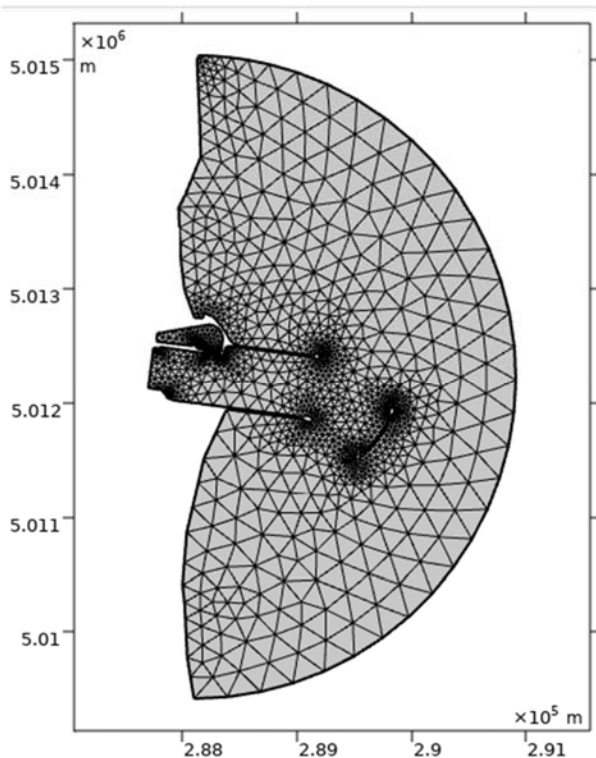


Figure 2 - Sample computational FEM grid for the Chioggia inlet

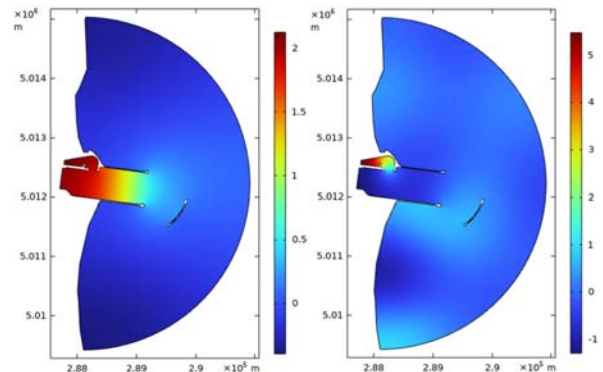


Figure 3 - Free surface elevation for two sample modes

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