Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Tidal Organ

Paulo Vaz de Carvalho

University of Aveiro, Department of Communication and Art
Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
paulo.carvalho@ua.pt

PACS: 43.75.-Z , 43.75.Np

ABSTRACT

In this paper we propose an original idea for using the energy of sea tides in order to provide adequate air supply to drive aerophones, for instance organs, located in public spaces near the shoreline. Beyond the basic aspect of suggesting an alternative power source for the air supply of such musical instruments, the proposed concept enables site designs and music performances with significant appeal and impact on visitors – for obvious aesthetical reasons but also because, by extracting its energy from the enclosing nature, the instrument is felt as being part of it. We start by reporting the developing process which led to the “Tidal organ” concept, and then describe in detail the basic setup, as well as a few design variations. Then we discuss various possible operating regimes of this energy supply system. Actually, following the general guidelines provided by the author, a “Tidal organ” project is currently being developed, to be built at “Estaleiro do Ouro”, in Porto, Portugal.

INTRODUCTION

Genius Loci and the art of sound

Genius Loci, a dominant concept in architecture, refers to a place’s potential to have an object built on, thus conditioning its meaning. It is a concept that does not end itself in the place’s functional or aesthetic adequacy but rather reaches its full meaning with the completion of the building either because of the place itself or the building’s attraction upon the visitors, making use of its potential be it of a visual, physical or social nature. The dialogue between the object being built and the place it is being built on is, thus, the third asset ensuing from that adequacy.

A building may establish a dialogue with the place through several links: a building’s image and meaning, its function, history, form and use of local energy. The genius locci manifests itself through different relationships between types of different architectural entities. For instance:

- In the Basilica of Superga the focus is on the geologic sculpture resulting from the difference of level between the city of Turin and the hill upon which this church is set;

- In “Falling Water”, Frank Lloyd Wright integrates the force of a cascade;

- In Portugal, the architect Alvaro Siza Vieira celebrates the respect for the freedom of the ocean designing Leça swimming pool with the only function of sustaining the waves and creating a safe environment for swimming;

- Windmills no longer used, as well as watermills, remind us of the ecological potential of the forces driving them;

- In Oslo, the mythical mermaid draws the attention to the poetical dimension of a confrontation between the land and the sea.

The poetics of Sound in the Landscape

In many places aeolic harps celebrate the force of the wind. On the other hand, ever since the Antiquity, water has always been an air pressure regulating element which feeds aerophones. These are therefore designated as Hydraulises. The brilliant use of air compression by force of the *waves* in Zadar, Croatia, is a state of the art reference as regards the symbolic use of a natural energy see Stamac (2005).

This instrument consists of a hydro-pneumatic chamber connected to the atmosphere by a set of beveled tubes. In the chamber there are a number of windows connecting it with the sea. The waves crash against those windows sealing them and compressing the air inside the chamber. The air thus compressed is expelled through the beveled tubes making them resound. The sound is stronger when the mass of water compresses the air in the cavity more rapidly and in a greater quantity, that is, when the sea is rougher. Not unlike the sea’s, its sound is incessant, even upsetting some of the visitors. This way this instrument gives us a sort of sound image of sea water movement. This is described in detail in a large number of internet sites (in particular www.grad-zadar.hr). Other sites are devoted to similar wave organs which were built in Blackpool, UK, and San Francisco, USA.

Nevertheless, even if wave energy has been used for driving organ pipes, to the best of our knowledge the energy of sea tides has never been used – or even suggested – for such purpose. This idea will be explored in the present paper.

DEVELOPMENT OF THE TIDAL ORGAN

Context

This work started when I was asked, by the architects Isabel Carvalho and Tiago Vidal, to design a project for an organ identical to the Zadar Organ, to be placed in "Estaleiro do Ouro", at the Douro River Estuary, in Porto, Portugal. Upon visiting the place I noticed that there were no waves, which was a disappointment and made me go back to the initial question of genius locci: which energy source exists in that place that can possibly create some sound or musical manifestation? Is there anything that can characterize and symbolize this place's geographical and historical identity? And how is it related to the lifestyle and history of the people living there?

I have identified two different sources of energy:
a) The wind, which although being common to many other places is not a unique feature of "Estaleiro do Ouro".

b) And the tides, which has always determined the Ouro inhabitants' life pace, who have been mostly fishermen, boatmen and ship owners.

The second option having been chosen, this posed a question: how to use that power and turn it into sound? And the answer was: through a closed chamber with a window at the bottom to allow the water of the tides to get in and out; at the top a collector should conduct the air making it flow through beveled tubes.

Process Development

A very elementary experiment was conducted with recourse to a bottomless demijohn, a plastic flute and a water bucket – see Figure 1.

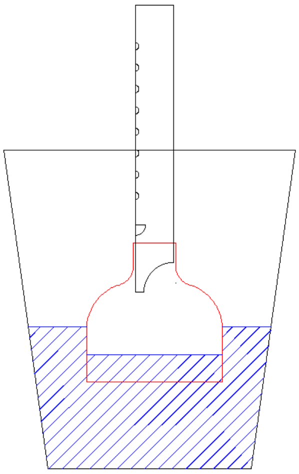

Figure 1. Elementary experience for illustrating the working principle of the "Tidal organ"

The flute was adjusted to the hole in the demijohn as if it were placed in the mouth of the flute-player. When one submerges the demijohn in the water contained in the bucket, the flute makes a sound until the level of the water inside the demijohn reaches the same level as in the exterior. The intensity of the blow decreases as the difference between the water level inside and outside the demijohn drops. The system's capacity limit is related to the air volume inside the demijohn.

In this basic design all the components are subject to the same relative motion between the water mass at the estuary and a fixed reservoir with a submerged window placed on the soil of the estuary – see Figure 2.

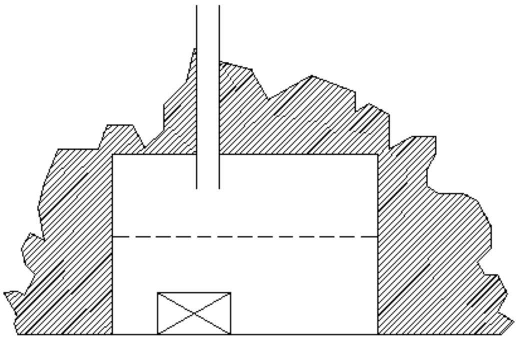

Figure 2. Basic design of a pressure reservoir for the "Tidal organ"

Bearing in mind that a 100 m long pier was being projected for the estuary, I suggested an enlargement of the system tested in the elementary experiment, using a liquid container submerged and tied to the estuary soil. This container should have a window at the inferior level and an exhaustion collector at a level higher than the level of the high tide.

As an alternative I also suggested digging a cavity on the pier, and building a window or a pipe, submerged to the level of the low tide, as well as an exhaustion collector with gas valves at the top of the cavity.

This cavity may be obtained through several processes:

a) A reservoir or set of reservoirs submerged and tied to the bottom by chains, or else set in concrete.

b) A building existent in the hydrographic space or in the pier dug cavity of a hollow box, with a window at the level of the soil.

c) By burying a chamber on the coastal zone outside the limits of the hydrographic mass, but connected to it through more or less long water pipes set at the level of the low tide and having an air duct system at the higher level.

All these processes make it possible to place the aerophones at some distance from the coast. Under these circumstances, which are similar from the viewpoint of their functioning, the water from the estuary enters through the window and when reaching the top prevents the air inside the chamber from getting out. From that moment on, the rising of the water causes a pressure increase inside the cavity whose inlet window is shut by pressure of the water itself.

Note that, because of the considerable pressure which builds as high-tide proceeds, any structural solution for the pressure containment must be designed with adequate strength. On the other hand, because organs and other aerophones need that air be fed at adequate pressure, it is imperative that the air supply from the reservoir be controlled through a suitable regulation valve.

WORKING REGIMES OF THE SYSTEM

Basically, the proposed system can function in a number of different ways:

1) If the air duct valves are open the air is directly expelled to the atmosphere without making any significant sound;

2) If, on the other hand, the air is expelled through a set of beveled tubes, it will produce a musical sound;

3) However, should the escape valves be shut, the air is retained and compressed at the rate of the difference between the tide level and the level of the water inside the reservoir.

As a consequence, the “tidal compressor” may feed one or more aerophones:

a) In real time, that is, as the tide rises. Through a system of communicating tanks placed at certain heights, it is possible to open and shut distinct types of tubes at different stages of the rising tide, and to get a sound reading of that stage of the tide.

b) Compressed air may be stored and later released by setting in motion a number of valves similar to those used in the cities for gas distribution – see Figure 3.

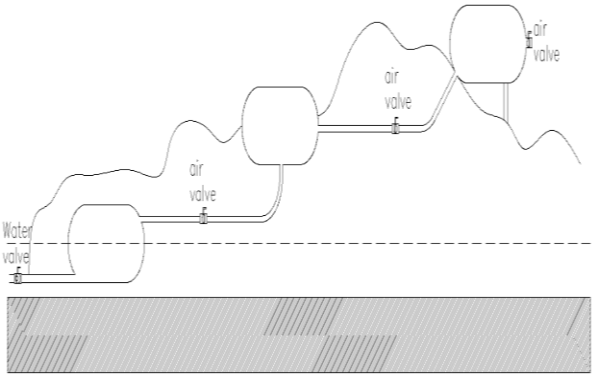

Figure 3. More involved system which includes several chained pressure reservoirs

c) This, on the other hand, leads to another possibility: that the aerophone fed by the tidal compressor may create music at any moment regardless of the tide stage. Instead of a sound or set of sounds cyclically produced according to the moment of the tide, one may use an aerophone to perform either a classic or a conventional repertoire, using the power of the tide even in the period after the rising tide.

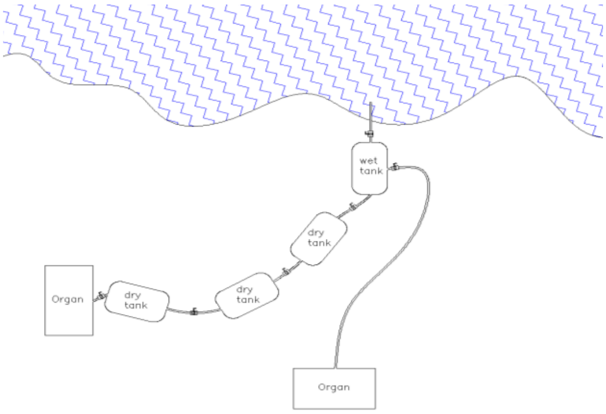

Figure 4. Illustration of a system setting with more than one aerophone

d) Finally, the hydro-pneumatic chamber (reservoir or cavity) may include a valve opening and shutting system to regulate the inlet water flow which, as it has already been explained, allows for a controlled timing of the system activity. This process appears to be very useful when one wants to obtain a strong water flow capable of originating a rapid air compression or an increase in pressurizing the air mass already retained in the chamber by force of the previous tide. This is also shown in Figure 3.

Setting of the system

Several aerophones may be tied to the air compressing network, as shown in Figure 4, and produce sound together or separately, which allows for the use of the location’s spatiality.

DIMENSIONS AND CAPACITY

Dimensioning parameters

One major design parameter is the amount of water likely to enter the cavity volume situated between the water window top and the highest level of the selected tide. In turn, the latter depends on the average area of the region contained between the referred levels. As shown in Figure 5, an increase in this regions’ volume causes the compressed air volume also to increase, despite the decrease of the compression rate, hence the pressure built.

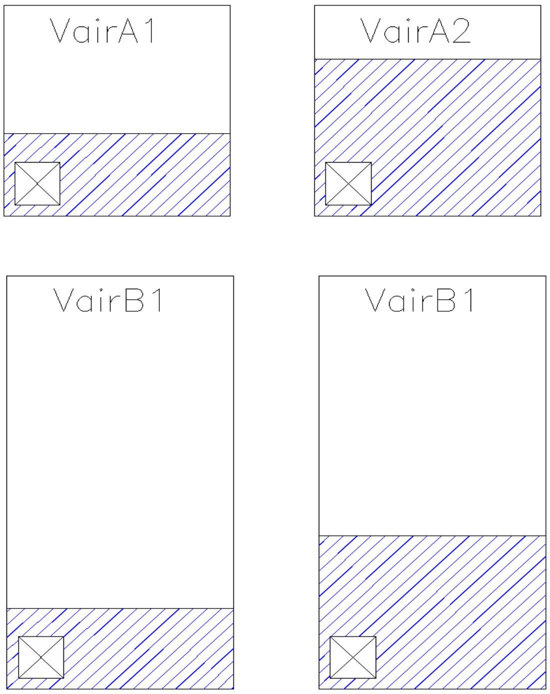

Figure 5. Rate of air compression for two reservoirs with different volumes

Air flow

Following the previous discussion, if air pressure is used in real time (as the tide rises), the pressure created in each cycle will depend on the ratio between the water volume entering the chamber and the air volume within the cavity at the beginning of the cycle – see Figure 6(a). The difference in volume of the region higher than the tide level may be obtained through a variation of the region’s height or of its cross-section. In an irregular cavity, the choice for one factor or the other may lead to oscillations in the flow rate, as illustrated in Figures 6(b) and 6(c).

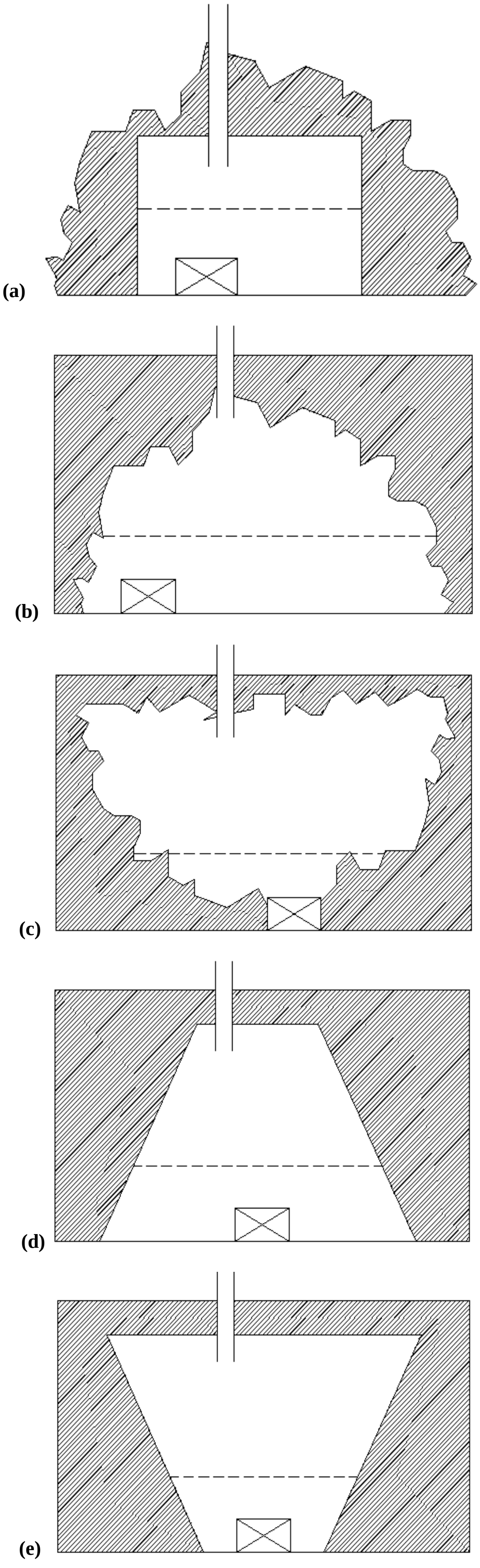

Figure 6. Examples of various reservoir geometries

The compression rate of the air inside the chamber increases faster in those chambers whose section decreases upwards – see Figures 6(b) and 6(d) – and slows down in those whose section decreases – Figures 6(c) and 6(e). Thus, in terms of the compression rate, a conical cavity shows a marked increase in time, unlike what happens when the cone is inverted. If the section is constant, as in Figure 6(a), the compression is also constant, provided the velocity of the rising tide remains constant, too.

Available pressure and air volume

For a reservoir with the air outlet closed (before the concert), the height of the water inside – hence the amount of air compression – may be easily quantified from simple fluid mechanics formulations.

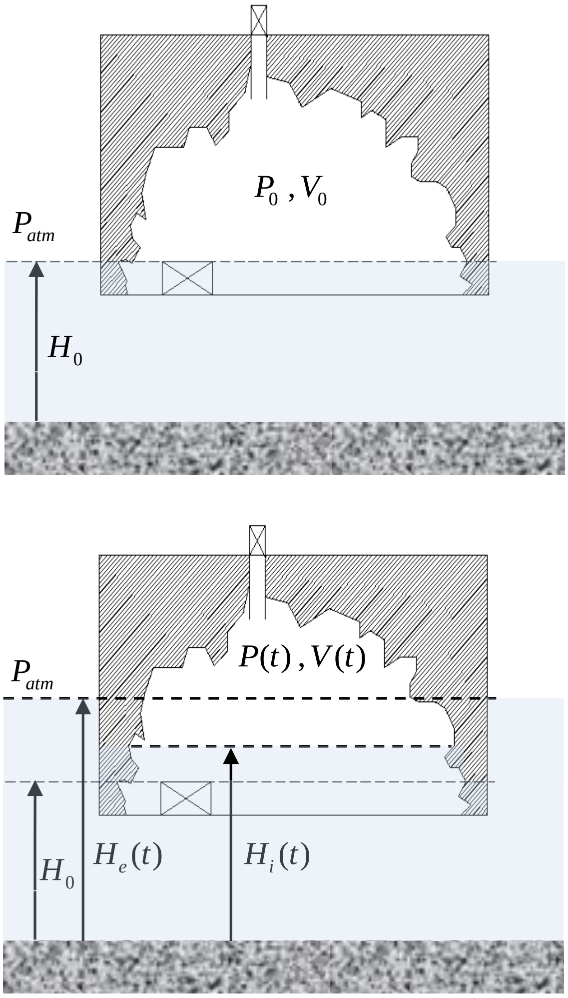

Figure 7. Parameters for computation of the fluid mechanics in the pressure reservoirs

In the upper scheme of Figure 7 is plotted a typical pressure reservoir, as well as the low tide level (assumed to be near the top of the inlet window). Outside, the water level is obviously at the atmospheric pressure P_{atm}. If the reservoir air outlet is closed under these conditions, then we will have the starting value of the air pressure inside $P_0 = P_{atm}$. Now, as the tide proceeds, the external water level increases as $H_e(t)$. Inside the reservoir it will increase less, up to a corresponding level $H_i(t)$, as shown in the lower scheme of Figure 7. The relationship between all these variables can be easily established, based on:

(1) Boyle's law relating the pressure and volume of a same amount of gas, as the container volume changes:

$$P\,V = \text{Const} \quad \Rightarrow \quad P_0\,V_0 = P(t)\,V(t) \qquad (1)$$

or:

$$P(t) = P_{atm}\,\frac{V_0}{V(t)} \qquad (2)$$

(2) The equilibrium of pressures at any given reference level, for instance H_0:

$$P_{atm} + \rho_w g\left[H_e(t) - H_0\right] = P(t) + \rho_w g\left[H_i(t) - H_0\right] \quad (3)$$

or:

$$P(t) = P_{atm} + \rho_w g\left[H_e(t) - H_i(t)\right] \qquad (4)$$

where ρ_w is the mass density of the water and g is the gravity acceleration.

Then, from equations (2) and (4), we obtain:

$$P_{atm}\,\frac{V_0}{V(t)} = P_{atm} + \rho_w g\left[H_e(t) - H_i(t)\right] \qquad (5)$$

where the internal gas volume $V(t)$ is a function of the internal water level $H_i(t)$ and of the specific geometry of the reservoir – namely, the change of the internal cross-section $S(y)$ with the vertical coordinate y:

$$V(t) = V_0 - \int_{H_0}^{H_i(t)} S(y)\,dy \qquad (6)$$

The simultaneous solution of equations (5) and (6) enables, for each specific geometry of the reservoir, the numerical computation of $H_i(t)$ and $V(t)$ as the tide height $H_e(t)$ proceeds. Then, for any given value of $H_e(t)$, the maximum pressure $P(t)$ available for "feeding" the aerophones is easily computed through equation (2).

If the reservoir geometry is simple, then equations (5) and (6) can be directly solved analytically. For instance, assume a cylindrical container with (constant) internal radius R, in the vertical position. Then, equation (6) becomes simply:

$$V(t) = V_0 - \int_{H_0}^{H_i(t)} \pi R^2\,dy = V_0 - \pi R^2\left[H_i(t) - H_0\right] \quad (7)$$

and we obtain from equations (5) and (7):

$$P_{atm}\,\frac{V_0}{V_0 - \pi R^2\left[H_i(t) - H_0\right]} = P_{atm} + \rho_w g\left[H_e(t) - H_i(t)\right] \quad (8)$$

whence $H_i(t)$ is obtained explicitly as a function of $H_e(t)$ through the analytical solution of the quadratic equation:

$$H_i(t)^2 - \left\{\frac{P_{atm}}{\rho_w g} + \left[\frac{V_0}{\pi R^2} + H_0 + H_e(t)\right]\right\} H_i(t) + \\ + \left\{\frac{P_{atm}}{\rho_w g} H_0 + \left[\frac{V_0}{\pi R^2} + H_0\right] H_e(t)\right\} = 0 \qquad (9)$$

Then, the internal air volume is obtained from equation (7), as a function of $H_e(t)$ and, finally, the driving pressure is computed from equation (2).

When the outlet valve in the reservoir top is opened, air flow will be generated – as intended – to supply the aerophones. In order to compute the features of such flow, one needs estimates of the pressure losses in the supplying pipe network, as well as of those within the instrument, for various playing scenarios which depend on the type and size of the aerophone: the registrations used, the level of polyphony complexity, and so on. Once information on such pressure losses is available, computation of the average "feeding" air-flow rates becomes a trivial routine – see for instance Durst (2008) or Munson et al. (2010), among many other books on the subject.

Working regimes

In a previous section we already addressed the various manners in which the "Tidal organ" may function. The main working regimes will now be discussed in correlation with the shape and capacity of the reservoir.

a) Real time performance regime: The flow rate of the air supplying system, in real time, will reveal any irregularities in the shape of the container, following the previous formulation, even when the movement of the rising tide is deemed regular.

b) Air retention regime: The compressed air in the stocking system will not be subject to the chamber section variables mentioned before. The effect of air retention from previous tides may be added to the "real time performance" during a later tide.

c) Retarded water entry regime: The entering of the water through the window may also be controlled or even slowed down in case one wishes the aerophone to function after a certain tide has risen. A tide's air retention effect may also be added to the effect of the slowed down entering of water.

Therefore, with the proposed system it is possible to accumulate the energy from two or more tides. In case one chooses a design based on the low pressurizing of a great air volume – using a large chamber extending well above the high level of the tide – the depressurization resulting from exhaustion, during playing, will be compensated from the moment a new rising tide generates pressure higher than the one of the air retained in the reservoirs. This process requires that both the compression chambers and the retention ones be working in a valve-controlled chain system.

As should be obvious to the reader, by now, it is the pressure in the chamber and not its volume that is responsible for the water not getting in. Consequently, whenever the tidal water mass generates a pressure that is higher than the pressure of the air retained, the system will continue working. The limit of the air volume accumulated, necessary for a non-stop performance, does not depend on the compression chamber volume but rather on the volume of all reservoirs – either recycled from previous facilities or set newly on the coast – which are linked to each other.

Timings

Stemming from the previous discussion, we now synthesize the time-scales of various possible functioning cycles of the "Tidal organ".

a) Simultaneous compression and performance—one tide period;

b) Successive compression, retention and performance—one tide period;

c) Accumulated retention, compression and simultaneous performance— more than one tide period;

d) Accumulated retention, compression and pre-recorded performance— more than one tide period.

Finally, as previously discussed, the maximum performing time of an organ, or other Aerophone fed by such a system, varies according to how much air the instrument being used needs. Again, we should stress that performance depends on the following factors:

- The aerophone's registration, which determines the tone as well as the sound volume of the pieces to be played;

- The polyphonic density of the pieces to be played – for instance, a fugue in four voices requires more air than a prelude of arpeggios.

CONCLUSION

We proposed in this paper an original idea for using the energy of sea tides in order to provide adequate air supply to drive aerophones, for instance organs, located in public spaces near the shoreline. After reporting the developing process which led to the "Tidal organ" concept, we described in detail the basic setup, as well as a few design variations. Then we discussed various possible operating regimes of this energy supply system, in connection with the relevant geometrical and tidal parameters. Following the general guidelines provided by the author, a "Tidal organ" project is currently being developed, to be built at "Estaleiro do Ouro", in Porto, Portugal.

ACKNOWLEDGEMENTS

I gladly acknowledge the technical support from my son Pedro Vaz de Carvalho, as well as useful discussions with the researcher Jose Antunes, from the Institute of Nuclear Technology, Portugal.

REFERENCES

I. Stamac (2005), "Acoustical and Musical Solution to Wave-Driven Sea Organ in Zadar" *2nd Congress of Alps-Adria Acoustics Association* and *1st Congress of Acoustical Society of Croatia*, pp. 203-206, 23-24 June 2005, Opatija, Croatia.

F. Durst (2008), "Fluid Mechanics: An Introduction to the Theory of Fluid Flows", Springer-Verlag, Berling, Germany.

B.R. Munson, D.F. Young, T.H. Ohiishi, W.W. Huebsch (2010), "Fundamentals of Fluid Mechanics", John Wiley and Sons, Hoboken, USA.