APPROACHING THE PHENOMENON OF FLOW INDUCED CONVERTER SLOPPING BY ANALYTICAL CONSIDERATIONS, NUMERICAL SIMULATION AND COLD EXPERIMENTS

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Abstract

Flow induced slopping represents a severe problem in operating AOD converters since high dynamic torques are introduced into the foundation via the torque support. In the long run, this could lead to unacceptable wear of the support bearings.

During this study the phenomenon of flow induced slopping has been studied by means of (a) analytic considerations, (b) cold water experiments and (c) numerical simulations. Based on a simply tank model that is mounted on a set of load cells characteristic slopping modes and frequencies are detected.

In a first example, a collapsing water column is considered. In this case it could be shown that all three investigation methods lead to very similar results with respect to the slopping mode and the slopping frequency. In the second case the bath is excited by gas injection. In that case numerical simulations are not straightforward since they have to cover the gas plume behaviour as well as a free surface flow. Thereby, it could be shown that while Reynolds averaged turbulence models suppress slopping the combined effect could be resolved by a multi-phase large eddy model.

1. INTRODUCTION

In steel works, argon-oxygen-decarburization (AOD) process is used in stainless steel making and in the production of other high-grade alloys. After the melting procedure, the metal is put into an AOD vessel where a great amount of oxygen mixed with argon is blown in through nozzles at the sides and the bottom. Repeatedly, accelerated wear of the support bearings, because of unacceptable high oscillating loads, has been observed. According to previous studies [e.g. 2] a reason for these loads might be intensive gas injection into the vessel. The uprising gas bubbles might trigger an unsteady wave pattern, which in turn might excite the mechanical system at its characteristic frequency.

In the present study, the characteristics, especially the frequency, of the excited waves have been studied by two different cold-water experiments. For both the test set-up comprises a simply tank model, which is mounted on a set of load cells. Thus, the frequency spectrum of the resulting wave pattern can be readily measured. In the first experiment, the frequency of a gravity wave induced through a collapsing water column is measured in dependence on the fill level of the tank. Secondly, the experiment is also simulated numerically with the software package OpenFOAM®. Finally, the mean slopping modes and slopping frequencies are studied analytically by potential flow theory. Thus, in case of the first experiment analytic, numerically simulated and experimental results can be compared with respect to the slopping mode and the slopping frequency.

During the second experiment, slopping waves are excited by gas injection through a nozzle mounted at the bottom of the tank. In the case of gas injection there is no analytic solution available and numerically
simulation are not straightforward since they have to cover the gas plume behaviour as well as a free surface flow.

2. EXAMPLE 1: COLLAPSING WATER COLUMN

2.1 EXPERIMENTAL CONSIDERATION

The test set-up is a tank with length 0.6m, width 0.2m and height 1m that is mounted on four load cells to measure the oscillating load caused by the slopping. For later analysis, the measured values of the two left respectively right sensors are averaged in order to obtain a quasi two-dimensional load monitor.

The excitement of the wave pattern is realised by a collapsing water column, which is created by a rectangular, evacuated body (see Fig. 1). During the experiment the time-dependent load signals on both sides of the tank are monitored. After an FFT analysis of these monitors a characteristic frequency of the wave pattern can be identified (see Fig. 2). Since, the fill level of the tank varies from 5 to 30cm, also the flattening section of the frequency curve at higher fill levels can be shown (see Fig. 5 and 6).

![Fig 1: Collapsing water column for 5 cm fill level; before starting experiment (left); excited wave (right)](image)

![Fi 2: Fast Fourier Transformation (FFT) from the experiment shown in figure 1](image)

3. NUMERICAL SIMULATION

The numerical simulations are done with the open source program OpenFOAM® that contains a standard solver ‘InterDyMFoam’ for two incompressible, isothermal and immiscible fluids using a Volume of Fluid (VOF) method.

The simulation of the collapsing water column represents a multiphase simulation with water and air. On the one hand the initial mesh is quite coarse in order to reduce simulation time. On the other hand a dynamic
grid refinement algorithm improves the resolution of the interface between water and air every time step (see Fig. 3). Moreover, a variable time step – adjusted in dependence on the Courant number – advances the stability and convergent of the simulation.

In the course of an unsteady simulation the loads on the tank are monitored and the characteristic frequencies are evaluated as described in the experiment.

![Initial grid for fill level 15cm (left); domain with refined grid after 0.5s (right)](image)

**Fig 3**: Initial grid for fill level 15cm (left); domain with refined grid after 0.5s (right)

### 4. ANALYTIC CONSIDERATION

For a rectangular tank with width $a$, length $b$ and fill level $h$ potential theory gives the possibility to calculate the frequency of a so called “gravity wave” [1]. This kind of wave and its characteristics are dependent only on the gravity force and no other external forces. In case of the collapsing water column, it is possible to describe the excited wave, but not the excitement itself. Assuming that at walls the normal velocity component must be zero, i.e. $v_z = \partial \phi / \partial z = 0$ for $z = -h$, $v_x = \partial \phi / \partial x = 0$ for $x = 0, a$ and $v_y = \partial \phi / \partial y = 0$ for $y = 0, b$, we get the result

$$\phi = A \cos(\omega t) \cosh(k(z + h))$$

for a stationary wave. Here $\omega$ is the circular frequency of the wave, $k$ is called the wave number and $A$ is the amplitude of the wave. From the boundary condition at the free surface, we find the relation between $k$ and $\omega$ to be

$$\omega^2 = gk \tanh(kh).$$

Moreover, it can be shown that possible values for $k^2$ are

$$k^2 = \pi^2 \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right),$$

where $m, n$ are the mode of the wave (integers) in $x$ respectively $y$ direction.
5. CONCLUSION

In case of the first example, a comparison between analytic considerations, experimental investigations and numerical simulations shows that all three approaches lead to very similar results for the frequency of the propagating wave. (Fig. 5 and 6)

**Fig 4:** Second mode of a stationary wave in a rectangular tank with length 0.6m, width 0.2m and fill level 0.1m

**Fig 5:** Compare of analytic, simulated and experimental results for occurring frequencies of a gravity wave (1\textsuperscript{st} mode)

**Fig 6:** Compare of analytic and experimental results for occurring frequencies of a gravity wave (2\textsuperscript{nd} mode)
6. EXAMPLE 2: GAS INJECTION

For gas injection experiment a single nozzle is mounted at the bottom of the tank. Through this nozzle compressed air is injected in order to induce a wave pattern. Once again, the data of the four load cells and the volume flow are measured to calculate the frequencies dependent on fill level and gas flow.

The first experiments with the second test set-up has shown that the frequency spectrum of the excited waves contains characteristic modes of gravity waves (1st and higher modes), but for more accurate results and conclusions it is too early, because the experiments are still in progress.

![Fig 7: Nozzle mounted at the bottom of the tank (left); Gas injection through nozzle (right)](image)

7. CONCLUSION

Motivated by slopping events during operation of AOD converters simple slopping experiments have been performed in a simplified rectangular water basin.

Based on a collapsing water column experiment it could be shown that all three investigation methods – analytic considerations, experiments and numerical simulations – lead to similar results with respect to slopping modes and frequency.

Future work will be dedicated to experiments focusing on gas injection induced bath slopping.

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LITERATURE