# Parametric Rolling of the Tumblehome Hull using CFD

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**ABSTRACT**

Parametric rolling is one of the five failure modes introduced by the draft amendments to IMO's 2008 IS Code. The aim of this paper is to study the use of CFD for the detection of parametric rolling. The ONR Tumblehome model 5613 was utilised and the simulation was set up using an overset mesh to allow motions to all 6 degrees of freedom. The results were validated against results presented from previous research. A number of different simulations were run and the results are presented and discussed herein.

**Keywords:** *parametric rolling, tumblehome hull, computational fluid dynamics*

## 1. INTRODUCTION

The tumblehome hulls main feature is the inward sloping freeboard. This is where the ships beam is wider at the waterline and becomes narrower towards the deck. This is in contrast to conventional flared and wall-sided hull designs.

The design was used heavily in warship design for the French and Russian navies in the early 20th century, the most notable being the Russian cruiser Aurora. However due to the hulls disadvantage in stability compared to other vessels, the hull design was eventually discontinued from mainstream vessels.

However with recent developments and a greater knowledge of ship stability and behaviour in certain sea environments, the Tumblehome Hull has returned to development in the form of a Naval Combatant.

The main reason for its return to service is due to its stealth capability and its wave-piercing bow. Though there has been a huge development of ship behaviour in different sea-types, for stability it has been noted that the Tumblehome is still at a disadvantage (Hashimoto, 2009).

## 2. BACKGROUND

### 2.1 Stability Issues

As the Tumblehome hull heels over, the waterplane area decreases resulting in the metacentric height decreasing. Therefore, though the GZ curve increases initially with heel angle, it very quickly begins to decrease reaching the angle of vanishing stability. Additionally with a lower metacentric height, the righting arm will be smaller, taking it longer for the hull to recover to its upright position (Hashimoto, 2009).

### 2.2 Parametric Rolling

A symmetrical ship moving in head seas is expected to have pitch, heave and surge motions according to the linear theory, but no roll. However due to non-linear effects, roll motions can occur at certain encounter frequencies due to a combination of external and internal factors. This phenomenon is called "auto parametrically excited motion" or "parametric motion" in short to indicate that the motion is the result the periodic variation of certain parameters of the oscillating system rather than the outcome of a time-varying external force (France, 2001). Once this roll motion has commenced, it can grow to large amplitudes (see Figure 1) and in extreme cases, may result in the loss of the vessel.

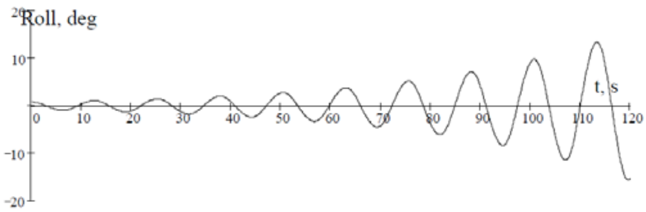


Figure 1. Parametric roll resonance (ABS, 2004)

Due to the restoring force of the tumblehome being smaller than comparable ships, it is therefore more susceptible to parametric rolling.

## 2.3 Criteria for Parametric Rolling

For Parametric Rolling to occur, the following conditions should be satisfied with the ship moving in pure head or following long-crested seas (France, 2001):

- The wave encounter period is approximately one-half the ships natural roll period
- The wave length is in the order of ship's length (0.8 to 2 times of LBP)
- The wave damping is below a certain threshold
- The wave height is above a certain threshold level

As the wave moves along the ship, the mean GM is smaller than conventional hullforms. Due to the relationship $\omega_n=\sqrt{(\Delta*GM/(I+A))}$, the effective natural frequency for parametric rolling to occur is smaller. Therefore the ship will encounter parametric rolling at low forward speeds. This is important, as roll damping is smaller at slower forward speeds, therefore the best course of action to avoid the phenomenon is to increase speed (McCue, 2007).

The IMO Second Generation Intact Stability criteria are developed in order to take into account stability failures that are not sufficiently covered in the 2008 Intact Stability code. The second generation criteria assess the vulnerability of the ship to parametric rolling as well as pure loss of stability on the wave crest, excessive accelerations, dead ship condition and Surfriding and broaching (Kruger, 2013).

There are various levels to investigate if a ship is vulnerable to parametric rolling resulting in a loss of stability. The Level 1 criterion is a conservative approach and involves a relatively simple calculation that the ship has to meet to show it is not vulnerable to the parametric rolling stability failure mode. It involves the variation of GM as the wave moves along the ship. If the criterion is not met in level 1, the ship in question should then be subjected to a more detailed assessment where it is required to meet the criteria for Level 2 criteria (Liu, 2014). If the ship fails to satisfy these criteria, then methods for the direct assessment of the stability of the vessels should be applied (Level 3).

## 2.4 Computer Fluid Dynamics (CFD)

Computational Fluid Dynamics approach can be a very useful tool for the study of the parametric rolling susceptibility of ships and a valid direct stability assessment (Level 3) method (Hosseini, 2011; IMO-SDC 2/INF.7, 2014). The software Star-CCM+ (CD-Adapco, 2015) was the tool used in the present study. The domain definition is shown in Figure 2.

It has had a positive response and is accredited for its ease of use by clients from across the industry. It has a user-friendly interface due to the automation of many functions and has many features that enable the program to tackle problems with complex shapes, such as the Tumblehome hull with its inward shaped bow.

It is capable of modelling Eulerian Multiphase, required for the interaction of the fluids air and water due to waves. It is also capable of simulating fifth order waves that are more representative of a real-life wave-pattern (CD-Adapco, 2015).

### 2.5 Overset mesh

In order to allow the ship to roll while encountering head waves, an overset mesh was required (see Figure 2).

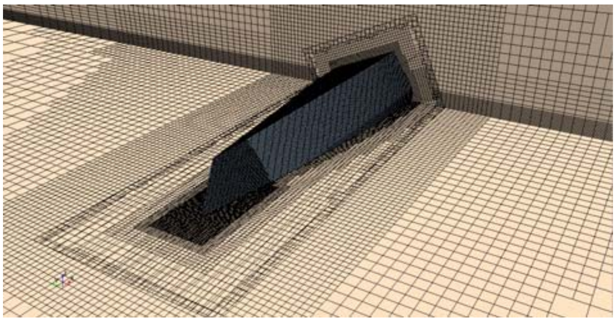

Figure 2. Rotated Overset Mesh

The domain (see Figure 3), where the simulation would take place was split in two; the fixed background was fixed and contained the freesurface and the overset containing the ship and was able to move as required in 6DOF. Both these meshes were able to interact allowing realistic waves and ship movements.

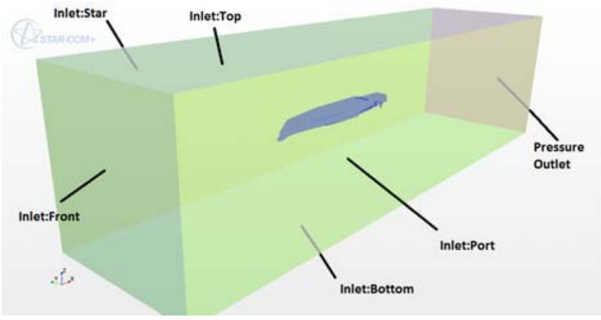


Figure 3. Domain definition

### 2.6 ONR Tumblehome model

The model used for the study was the ONR Tumblehome Hull model 5613 that was developed by Naval Surface Warfare Center, Carderock Division (NSWCCD) for ONR. (Bishop, 2005, Bassler, 2007)

The model used was based off the hull DDG-51, which is approximately half the size of the DDG-1000 Zumwalt Class. The tumblehome freeboard is angled inward 10 degrees from the vertical (Bishop, 2005).

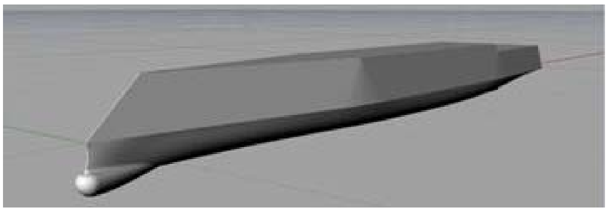

Figure 4. ONR Tumblehome Model without Bilge Keels

The dimensions used for the ONR Tumblehome hull are given in Table 1. For the simulation, the 1/32 model scale was utilised.

Table 1. Main Particulars of ship and model

| | Full-Scale (15C, SW) | | 1/32 Model-Scale (20C, FW) | |
|---|---|---|---|---|
| Lpp | 154 m | 505 ft | 481 cm | 15.8 ft (189.6 in) |
| Beam | 18.8 m | 61.7 ft | 58.8 cm | 1.93 ft (23.2 in) |
| L/B | 8.2 | 8.2 | 8.2 | 8.2 |
| Max. Depth | 14.5 m | 47.6 ft | 45.3 cm | 1.49 ft (17.8 in) |
| Max. Freeboard | 9.00 m | 29.5 ft | 28.1 cm | 0.92 ft (11.1 in) |
| Draft | 5.50 m | 18.0 ft | 17.2 cm | 0.56 ft (6.77 in) |
| Displacement | 8790 tonnes | 8650 LT | 261 kg | 575 Lbs |
| LCB (aft of FP) | 79.6 m | 261 ft | 249 cm | 8.16 ft |
| VCB (above BL) | 3.26 m | 10.7 ft | 10.2 cm | 0.33 ft (4.01 in) |
| $KM_T$ | 9.74 m | 32.0 ft | 30.4 cm | 1.00 ft (12.0 in) |

For the numerical simulations, the bilge keels were removed as can be seen in Figure 4. This was because they would produce a damping force that would prevent the occurance of parametric rolling and it will also increase the meshing requirements around them.

## 3. METHODOLOGY

### 3.1 Initial assessment

The full scale model was imported into the Maxsurf Stability software, (Bentely, 2014) where the position of the centre of gravity was inputted along with the parameters of the wave. The program was used in order to calculate the change in GM as the wave passes by the hullform. This change in GM (ΔGM) was used for the calculation of the Level 1 Vulnerability Criteria for Parametric Rolling. A ship was considered not to be vulnerable to the parametric rolling stability failure mode if (IMO SDC 2/WP.4, 2014):

$$(\Delta GM)/GM \leq Rpr \quad (1)$$

The result was (ΔGM)/GM=0.37 and Rpr =0.17, demonstrating the tumblehome hull without its bilge keels is failling the first criteria, making that the ship vulnerable to parametric rolling.

### 3.2 Simulation Setup

The simulation was run using an allocated 36 cores over two cycles taking approximately 48.3 hrs for a simulation time of 70 seconds. Therefore 1738.8 CPU hrs were required with each of the 35,000 iterations taking 2.98 minutes per iteration to complete. The ARCHIE-WeSt state-of-the art High Performance Computer was used for the runs (ARCHIE-WeSt, 2015) The hardware used includes Dell C6100 servers with Dual Intel Xeon X5650 2.66 GHz CPU's (6 cores each), having a RAM of 48 GB, linked by 4xQDR Infiniband Internconnect.

In total about 5 million cells were required to build up the simulation with 1.8 million cells required for the background domain and 2.9 million cells for the overset mesh. The file size was 2GB.

### 3.3 Wave Conditions and Ship's speed

The conditions used in the simulation were known to result in parametric rolling. They were set up as follows; the full scale wave encounter frequency was 0.8 rad/s, 4.6 rad/s in model scale. The waveheight in full scale of was 7.5m and 0.234m in model scale. The full scale wavelength was 154m, which resulted in 4.8125m in model scale. Finally, the Froude Number was 0.106.

### 3.4 Initiating roll

Due to the ship travelling in headwaves, rolling will not occur unless there is an initiating event. Two methods were used to initiate the roll motions of the ship. The first method involved the ship positioned in its upright position with an initial angular velocity of 0.1 rad/s exerted onto the model.

The second method again involved the ship in its upright position but involved a small shift of the transverse centre of gravity by 0.00156m to starboard.

When the model was released within the simulation after 0.5 seconds, both these methods would result in the ship rolling and parametric rolling would commence if the criteria for it to occur were met.

## 4. PARAMETRIC ROLLING WITH ANGULAR VELOCITY METHOD

### 4.1 Roll Motion

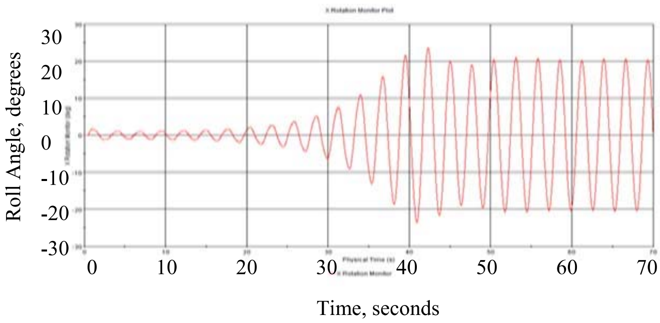


Figure 5. Parametric Rolling Pitch

It was found that the period between oscillations was 2.7s. This is double the wave encounter period of 1.35s, thus demonstrating that the ships motions meets the first criteria of parametric rolling as described in the above literature review (see Figure 5).

The first oscillation reached a peak heel angle of 1.75 degrees due to the initial angular velocity of 0.1 rad/s. The roll motion damped slightly with the following roll amplitude being ±1 degree. Over the next 20 seconds the roll amplitude for the following 6 oscillations remained relatively steady, increasing gradually over that time to an amplitude of ±2 degrees. The roll amplitude began to increase substantially with the 9th oscillation plotting a peak roll angle of 2.75 degrees, 10th – 3.5 degrees, 11th – 5.25 degrees, 12th – 7.5 degrees, 13th – 10.8 degrees, 14th – 14.75 degrees, 15th – 21.5 degrees and 16th – 23.5 degrees. For the 17th oscillation onwards, the roll amplitude damped down to an average of 20 degrees where it remained constant for the remainder of the simulation.

This demonstrated that after 45 seconds from the initial angular velocity, the ship encountered steady parametric rolling.

It is noted that with a GM of 1.5m, the vanishing angle of the Tumblehome hull is 64 degrees, therefore these parametric roll motions alone will not result in the loss of the vessel.

### 4.2 Pitch Motion

The values of pitch are initially large. However this can be explained by the simulation converging and the shock of the model being released as the subsequent pitch angles after 7.5 seconds had an average amplitude of 2.57 degrees (see Figure 6).

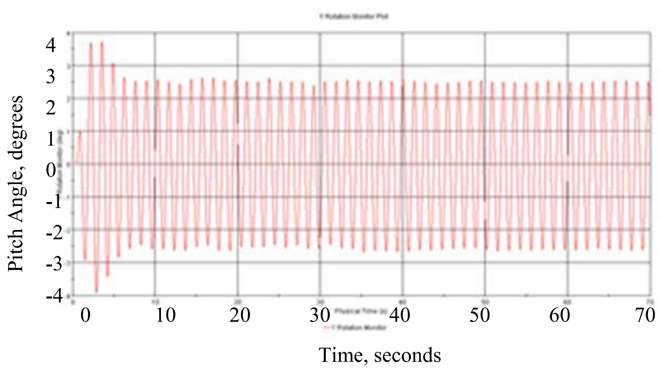


Figure 6. Parametric Rolling - Pitch

It was noted that the average peak pitch was 2.548 degrees while the average trough pitch was -2.587 degrees. Though the difference is 1.5% it does suggest the Tumblehome is following the pattern of diving rather than being lifted over the wave.

The large angles of pitch are coupled with the large angles of roll encountered during the parametric motion.

It is also noted that the pitch period was 1.36s, which is 4.61rad/s or 0.8 rad/s in full scale. This is identical to the encounter period of the wave, suggesting that pitch is dependent on the period of the wave.

### 4.3 Heave Motion

The heave amplitude of the model was 0.0275m, 0.88m in full scale. The ship heaved around a position of 0 to 0.02m throughout the simulation reaching an average value of 0.02m after 15s before stabilising at 0.01m (see Figure 7).

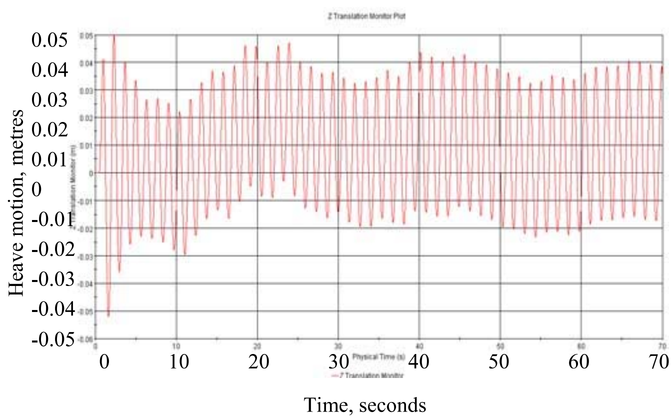


Figure 7. Parametric Rolling - Heave

This motion suggests that the ship is being lifted out the water during the motions of parametric rolling. The heave period was noted to be identical to the pitch and wave encounter period.

## 5. PARAMETRIC ROLLING WITH DISPLACED TRANSVERSE CENTRE OF GRAVITY

An additional method used to initiate roll in order to promote parametric rolling was moving the centre of gravity off the centreline and to starboard by 0.001486m, 0.0475m in full scale. It would also allow the motions of the ship to be compared with the motions resulted from the previous method.

### 5.1 Roll

It was again found that the natural roll period of 2.7 seconds was double that of the wave encounter period of 1.35s, confirming that parametric rolling is being detected. (see Figure 8). Parametric rolling became apparent as soon as the ship was released, with the roll amplitude increasing significantly for the first 7 oscillations. After the 8th oscillation, the roll stabilised indicating that the ship had reached its natural roll period with sufficient restoring.

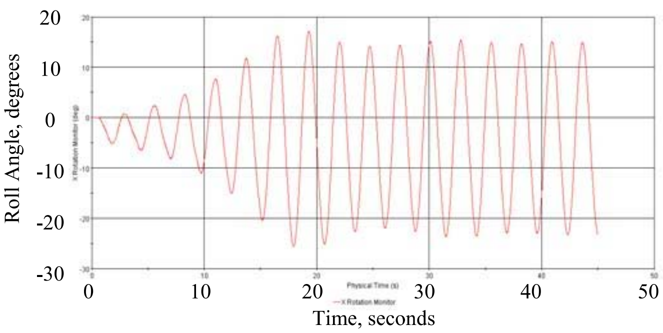


Figure 8. Asymmetric Parametric Motion - Roll

It was noted that steady parametric rolling is detected 20 seconds quicker in this method with the mass off the centreline than compared to the method with the mass on the centreline and angular velocity used to initiate roll.

The first oscillation rolled around the heel angle of -2.5 degrees and had an amplitude of 2.93deg. This amplitude increased to 4.43deg for the 2nd oscillation, 6.73 degrees - 3rd, 9.27 degrees - 4th, 13.36 degrees - 5th, 18.29 degrees - 6th and 21.35 degrees 7th oscillation. For the 8th oscillation the roll amplitude decreased to 20.06 degrees and then 18.37 degrees where it remained for the continuation of the simulation.

It was noted that the asymmetry of the roll increased from around -2.27 degrees to an average of -4.3 degrees when the rolling became constant.

The Angular Velocity of roll varies between 9 and -7 rads/s. As the roll velocity is at its maximum, the ship is at its upright position. When the velocity is at 0, the ship is at its maximum heeled angles.

### 5.2 Pitch

The values of pitch are initially large however this could be put down to the simulation converging and the shock of the model being released as the subsequent pitch angles after 7.5 seconds had an average amplitude of 2.57 degrees (see Figure 9).

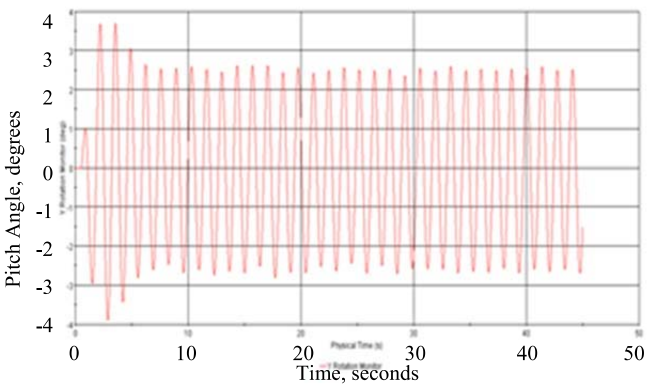


Figure 9. Asymmetric Parametric Motion - Pitch

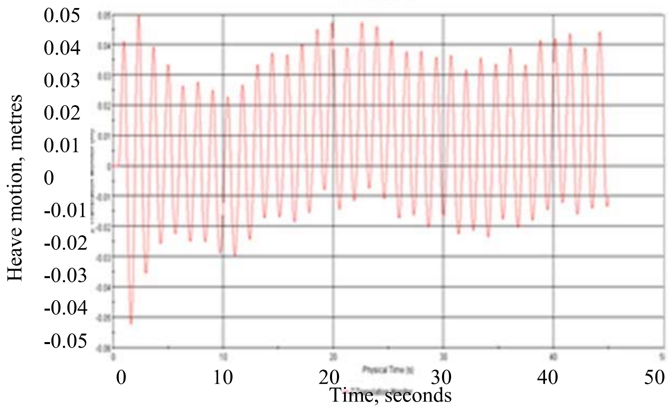


Figure 10. Asymmetric Parametric Motion - Heave

It was noted that the average peak pitch was 2.548 degrees while average trough pitch is -2.587 degrees. Though the difference is 1.5% it does suggest the Tumblehome is again following the pattern of diving rather than being lifted over the wave. The pitch period was noted to be 1.36s, which is 4.61rad/s.

### 5.3 Heave

The heave amplitude follows the same small values as the previous simulation and is again coupled with pitch. It is also noted that the heave motions are once more oscillating around a moving average that varies between -0.005m and 0.015m again showing that the ship is lifted out of the water (see Figure 10).

### 5.4 Comparison with Angular Velocity Method

It is noted that the motions of pitch and heave are very similar, regardless to the method used to initiate the roll. It was noted that in the mass off centre method, the parametric rolling was detected 20 seconds sooner, with the amplitude being slightly smaller at 18.37 degrees instead of the 20 degrees. Additionally with the mass off centre, the roll was subsequently asymmetric.

## 6. INCREASED SHIP SPEED

To investigate the change in parametric rolling and related motions, the ships velocity was increased to a Froude number of 0.145579, 11 knots in full scale. The wave encounter frequency was subsequently increased to 0.87 rad/s in full scale and 4.97 rad/s in model scale. The roll in this simulation was initiated with the mass off centre method.

### 6.1 Roll

The average period between oscillations was noted through tabulation to be 2.52 seconds, double the wave encounter period of 1.265s again demonstrating that the ship motion is meeting the criteria of parametric rolling. (see Figure 11)

The first oscillation rolled around the angle of -2.6 degrees and had an amplitude of 2.26 degrees. This amplitude increased to 2.51 degrees for the 2nd oscillation, 2.92 degrees - 3rd, 3.64 degrees - 4th and 4.69 degrees - 5th oscillation. Though the simulation was only run for 15 seconds, it was apparent that the increase in amplitude was significantly smaller with the amplitude only increasing by 107.5% by the 5th oscillation compared to 355.97% when the ship was travelling at a slower speed.

This corresponds with the literature, indicating that the faster the ship speed, the intensity of parametric rolling is reduced. Therefore, a solution to recover from the motion is to increase the speed of the vessel.

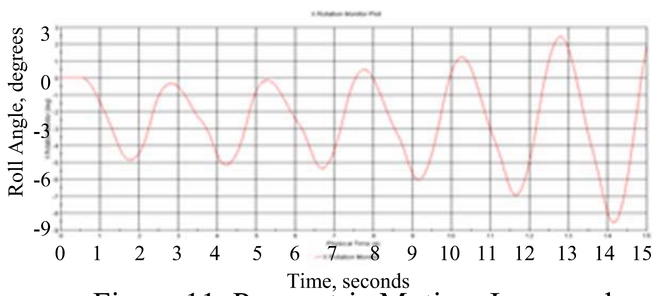


Figure 11. Parametric Motion, Increased Velocity, Roll

It was noted that the asymmetry of the roll for the first oscillation was -2.60 degrees. This increased to -2.65 degrees for the 2nd oscillation, but for the following oscillations, the asymmetry decreased progressively to -2.25 degrees.

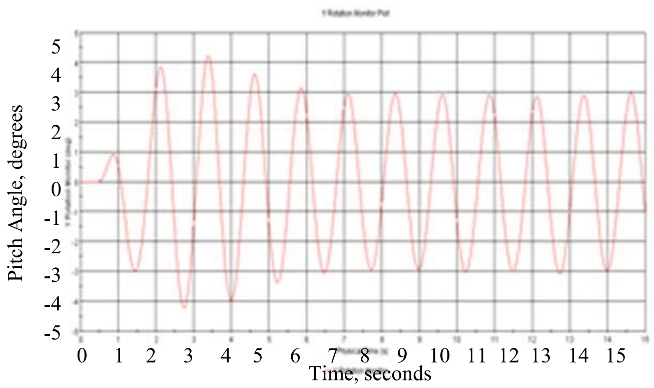


Figure 12. Parametric Motion, Increased Velocity Pitching

### 6.2 Pitch

It was noted that the pitch amplitude is 15.95% larger than the previous simulation with an amplitude of 2.98 degrees. This suggests that at faster velocities the tumblehome encounters its natural pitch period (see Figure 12).

### 6.3 Heave

The heave motion amplitude was found to be 0.037m, 1.184m in full scale. This is an increase in amplitude of 48% compared to parametric rolling at a lower speed.

It was noted that the heave motions are oscillating around a moving average that varies between 0.004m and -0.004m for the first 12s before increasing significantly (see Figure 13).

It was noted that though the coupled motion of pitch is larger due to the non-linear motions of roll being reduced, the heave motion is also larger.

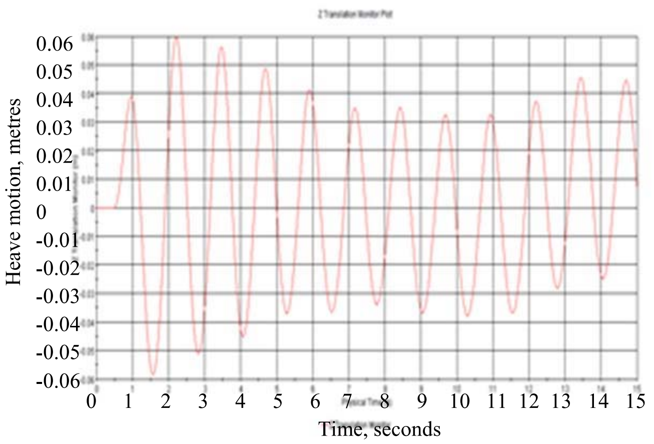


Figure 13. Parametric Motion, Increased Velocity Heaving

## 7. CONCLUSION

The aims of the stydy were met whereby using the CFD application Star-CCM+, the non-linear motion of parametric rolling was detected and analysed.

The simulation to find the motion was set-up from scratch using the ONR Tumblehome Model with the bilge keels removed and required an Overset Mesh to allow the essential movements of pitch, heave and roll. The GM for these simulations was set to 1.5m or 0.047m in model scale.

Parametric Rolling was detected at the model scale wave encounter frequency of 4.6 rad/s, Froude number 0.105 and a wave height of 0.234m. It took approximately 45 seconds for steady rolling to occur with an amplitude of 20 degrees. This motion was accompanied with high pitch angles and small heave motions.

It was found that steady parametric rolling occurred 20 seconds quicker when the centre of mass was displaced slightly to starboard than when the mass is above the centreline of the ship, though the roll was asymmetric and the amplitude was smaller at 18.37 degrees.

It was confirmed that when the ships velocity was increased from 8kn to 11kn, the intensity of parametric rolling decreased substantially with the roll amplitude increasing at a slower rate. This corresponds with other research involving parametric rolling, where a means of avoiding the non-linear phenomenon is to increase speed.

The study has proven that CFD can be a valuable tool for the investigation of this interesting and complex phenomenon and may assist the designers to develop ships “immune” to the risk of parametric rolling.

## 8. ACKNOWLEDGEMENTS

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