

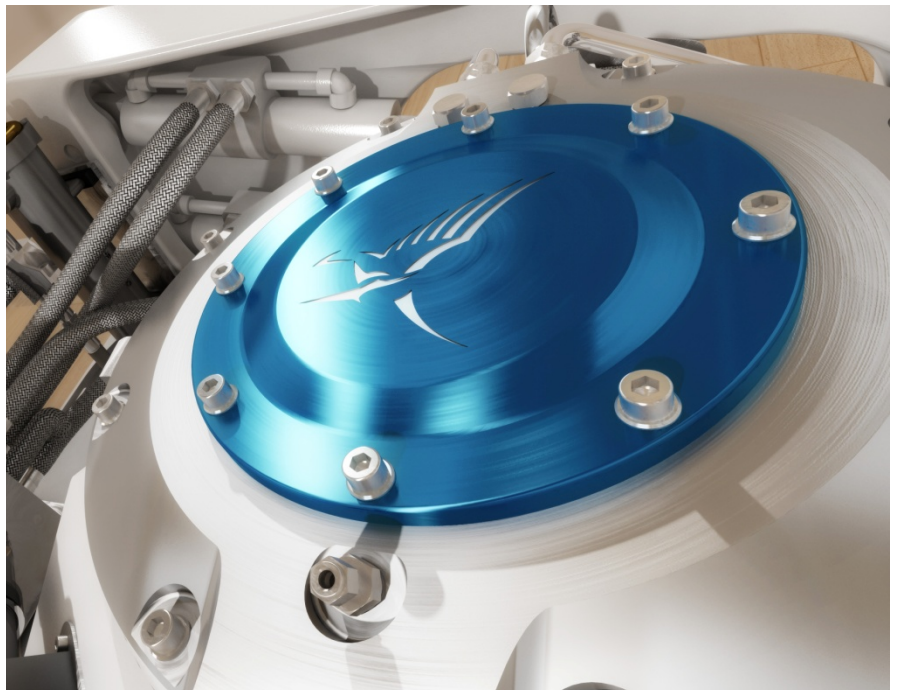


# How Gyros Create Stabilizing Torque

Whitepaper 1403

## Topics Covered :

- Coordinate System and Terminology
- How the Stabilizing Torque is Created
- Step by Step
- Calculating The Stabilizing Torque Delivered
  - Calculating Angular Momentum
  - Calculating Precession Rate
  - Calculating Gyro Torque and Stabilizing Torque
- What Next?



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## How Gyros Create Stabilizing Torque ...

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This article has been prepared with the aim of explaining exactly how marine gyro stabilizers create stabilizing torque, using diagrams and only basic mathematical formulae. This article is intended for technical people with a basic working knowledge of mathematics and physics.

The formula provided will allow the calculation of basic operating parameters of a gyro stabilizer for those interested.

Please let me know if you found this article useful. I can be contacted at [gyro@veem.com.au](mailto:gyro@veem.com.au)

Paul Steinmann.

### Some Resources

There are a lot of videos and articles online that attempt to describe flywheel precession. The video I think comes closest can be accessed on YouTube at:

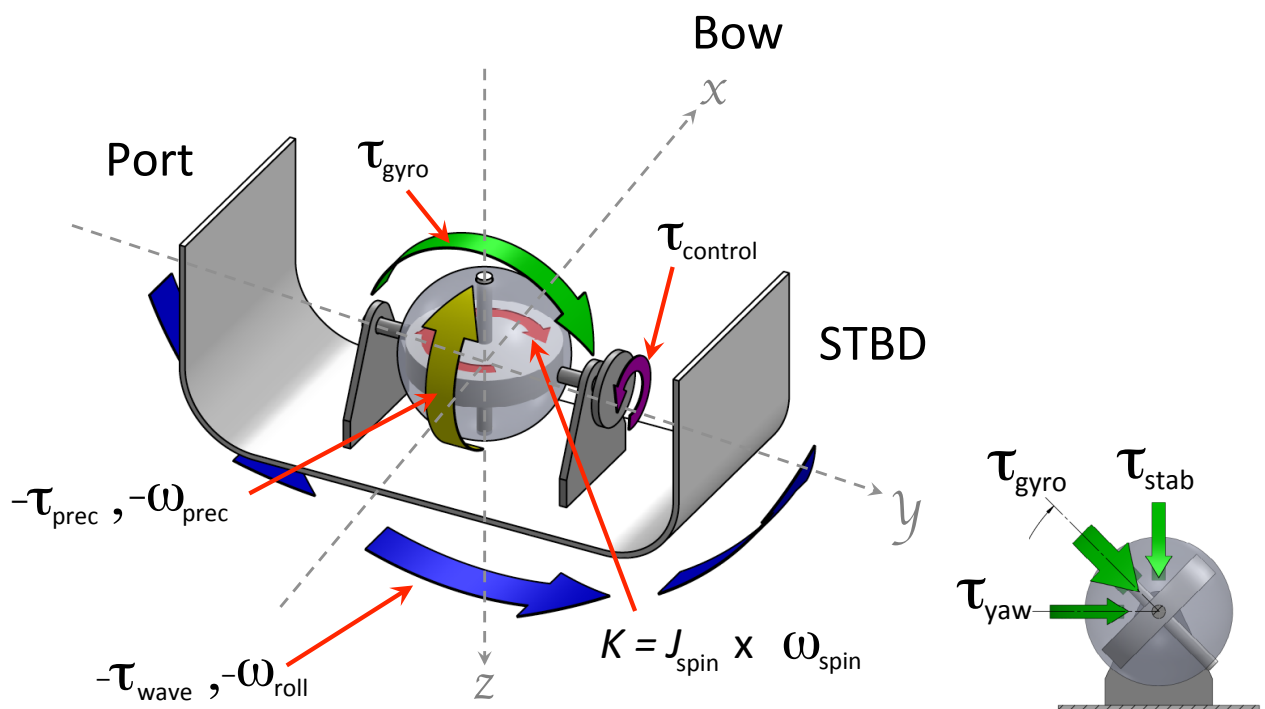
<https://www.youtube.com/watch?v=TUgwaKebHTs>

There are also numerous descriptions of the physics of gyroscopes available, such as this one:

<http://www.real-world-physics-problems.com/gyroscope-physics.html>

## Coordinate System and Terminology

Symbol	Description	Coordinate Sense	Units
$x$	Surge axis	Positive forward	m
$y$	Sway axis	Positive to STBD	m
$z$	Heave axis	Positive down	m
$\omega_s$	Flywheel spin rate	+ve clockwise looking down	rpm or $\text{rad.s}^{-1}$
$\omega_p$ or $\dot{\alpha}$	Flywheel precession rate	+ve rocking forward	$\text{deg.s}^{-1}$ or $\text{rad.s}^{-1}$
$\alpha$	Flywheel precession angle	+ve rocking forward	deg or rad
$\dot{\theta}$	Vessel roll rate	+ve to STBD	$\text{deg.s}^{-1}$ or $\text{rad.s}^{-1}$
$\theta$	Vessel roll angle	+ve to STBD	deg or rad
$\tau_{wave}$	Wave Induced Rolling Torque	+ve to STBD	kNm
$\tau_{gyro}$	Gyro torque	+ve to STBD	kNm
$\tau_{prec}$	Precession torque	+ve rocking forward	kNm
$\tau_{stab}$	Stabilizing torque	+ve to STBD	kNm
$\tau_{yaw}$	Yaw torque	+ve bow to port	kNm
$\tau_{control}$	Precession Control Torque	+ve Bow up	kNm
$J_{spin}$	Flywheel Rotational Inertia	n/a	$\text{kg.m}^2$



## How the Stabilizing Torque is Created

Vessel rolling motion is created or induced by forces acting on the hull by passing waves. In order to resist and reduce this rolling motion, torque acting in the opposite direction to the wave induced rolling torques must be generated. This is true of all stabilizing systems, including fins, flume tanks, flopper stoppers, moving mass systems, magnus-effect systems etc.

The challenging thing about grasping exactly how a gyro stabilizer works is understanding how the roll-opposing torque is generated when there is nothing in the water to create a force. There are two ways that a spinning flywheel can be configured in a yacht to act as a stabilizing system. The flywheel spinning axis can be set vertical, and the cage that holds the flywheel axle bearings can be allowed to rotate in a vertical fore and aft plane (the pitch axis of the yacht). Alternately, the flywheel's spinning axis can be set horizontal and aligned athwartships (across the hull from side to side), and the cage that holds the flywheel's spin bearings can be allowed to rotate in the horizontal plane (the yaw or heading axis of the yacht). Both of these arrangements will cause rolling motion to be opposed by the gyro. A number of practical considerations combine to select the best of these two arrangements. More on this later.

There seems on first appraisal to be nothing for the gyro stabilizer to leverage against to create stabilizing torque. However as we will see, basic physics explains that the seemingly miraculous behaviour is perfectly normal. The primary concept that must be grasped is that once a flywheel is set spinning and therefore has angular momentum, this momentum can be used to counteract vessel rolling motion. If a spinning flywheel is caused to rotate with angular velocity by a couple acting on the spin bearings, the resulting rotational rate (not the applied torque, but the resulting rate of rotation) creates or induces a torque in a plane that contains the spin axis and is perpendicular to the plane of the applied torque. In this way the applied torque appears to be bent through 90°. However the relationship is specifically between the precession rate, the angular momentum of the flywheel, and the gyro torque produced. This relationship is elegantly simple and can be written in mathematical form as follows:

Gyro Torque = Angular Momentum x Angular Velocity

$$\tau = J_{spin} \times \omega_{spin} \times \omega_{prec} \text{ [Nm]}$$

where,

$\tau$  is the gyro torque [Nm]

$J_{spin}$  is the flywheel rotational moment of inertia about the spin axis [kg.m<sup>2</sup>]

$\omega_{spin}$  is the spin speed or spin angular velocity [rad.s<sup>-1</sup>]

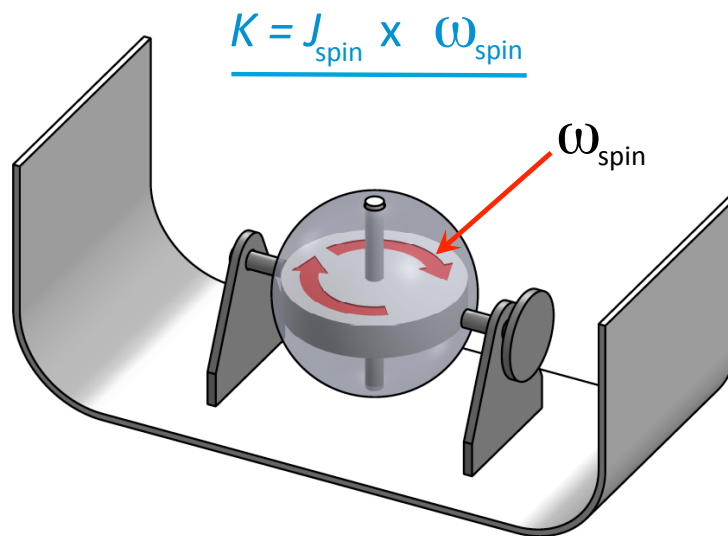
$\omega_{prec}$  is the precession angular velocity or precession rate [rad.s<sup>-1</sup>]

## Step by Step

A brief outline of the operating principal of VEEM Gyros is as follows:

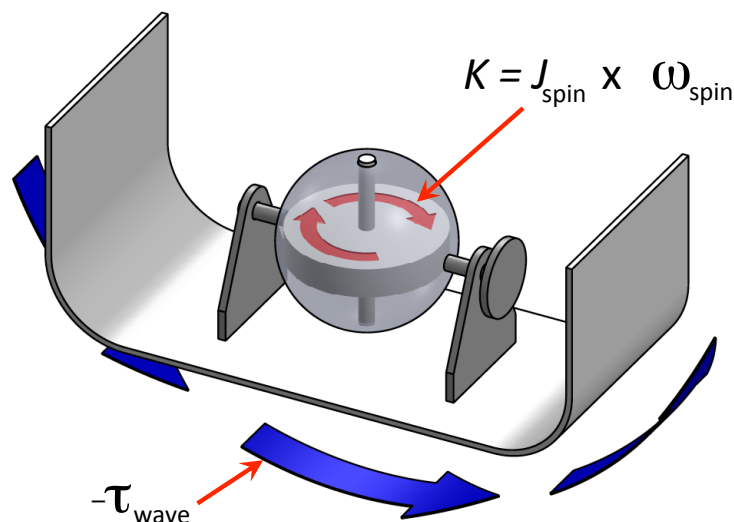
### 1. Flywheel RPM Creates Angular Momentum

The flywheel is spun up to speed, with the precession axis locked. The flywheel now has angular momentum ( $K$ ) equal to the rotational inertia ( $J_{spin}$ ) of the flywheel times the spinning speed ( $\omega_{spin}$ ). With the precession axis locked, and no vessel rolling motion, there is no stabilizing torque produced.



### 2a. Waves Induce Rolling Torque

Waves passing under the vessel induce rolling torque on the hull of the vessel due to buoyancy forces and other force components.

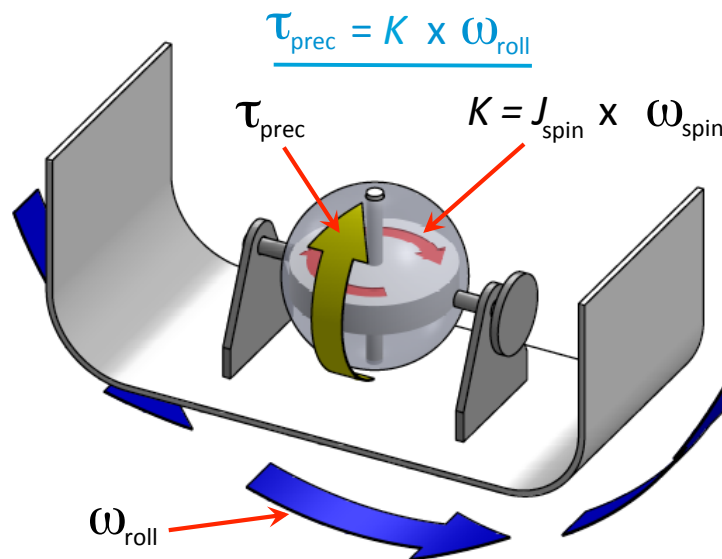


### 2b. Vessel Responds by Rolling

Rolling motion occurs (roll angle, roll velocity and roll acceleration) depending on the wave elevation, the vessel's mass distribution and shape of the hull. With the precession axis locked, no stabilizing torque is produced, but the precession brake does have to resist precession torque induced by the product of the roll rate and the flywheel angular momentum.

### 3a. Roll Rate Generates Precession Torque

The angular roll rate ( $\omega_{roll}$ ) combines with the flywheel angular momentum ( $K$ ) to generate a precession torque ( $\tau_{prec}$ ) on the flywheel (in the yacht's pitching axis). Note that it is NOT the wave induced rolling torque that directly induces the precession torque, but the rate of roll. Note also that the roll rate ( $\omega_{roll}$ ), angular momentum ( $K$ ) and resulting precession torque ( $\tau_{prec}$ ) are all at right angles to each other as this is a vector cross product.

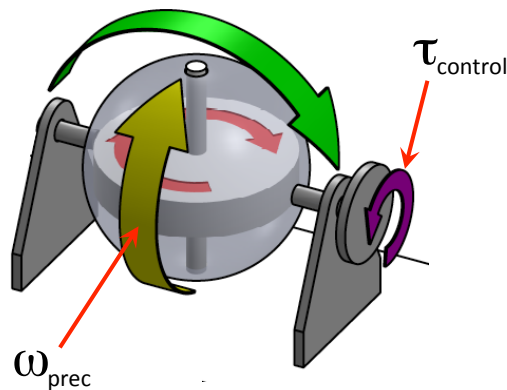


### 3b. Flywheel Precesses with Precession Rate

Once the precession brake is released, the flywheel responds to the induced precession torque by precessing. It is important to note that there is no active or passive control required to create this precession, it occurs due to the gyroscopic effect). The precession rate (the rotational speed of precession) induced by the precession torque depends upon the inertia, damping and stiffness of the assembly suspended by the precession bearings.

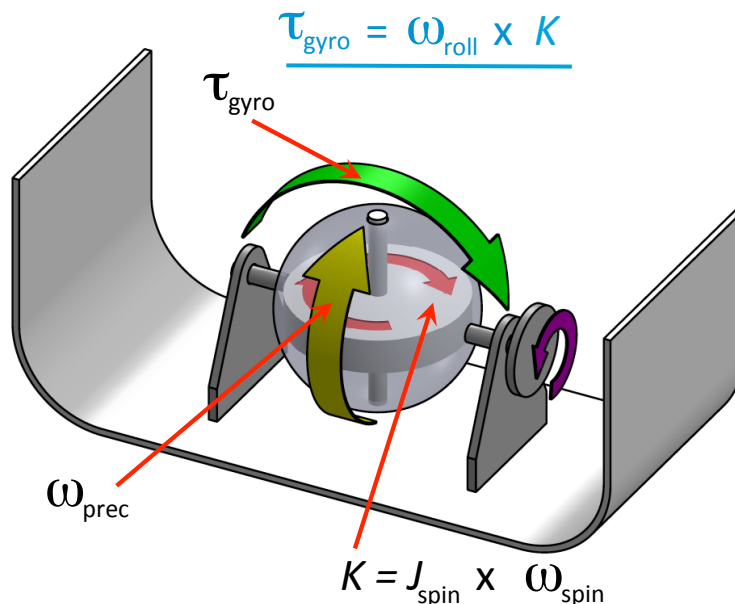
## 4. Control System Actively Adapts to Optimise Precession Rate

The control system manages this naturally occurring precession motion to ensure that it is maximized within the operating limits of the device. The operating limits are set during product design, and include precession range of movement, and maximum allowed precession rate. These design operational limits are important as they define to a great extent the competitive performance differences between various gyro stabilizer market offerings.



## 5. Precession Rate Generates Gyro Torque

The rate of precession motion ( $\omega_{prec}$ ), combined with the flywheel angular momentum ( $K$ ), induces a 'gyro torque' that acts in a plane that is athwartships (across the width of the vessel) and includes the spinning axis (so the plane rotates with the flywheel precession).

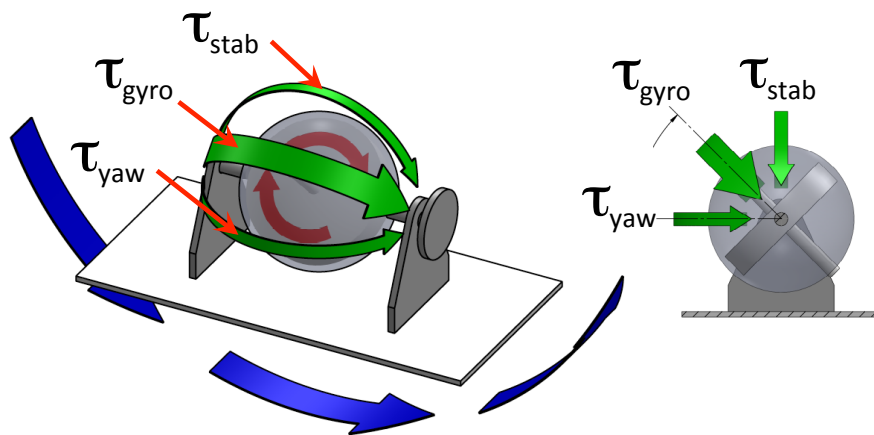




## 6. Stabilization Torque is Component of Gyro Torque in Roll Axis

When the spin axis is vertical, all of this induced gyro torque is roll stabilization torque

When the spin axis is rotated away from vertical, most of the gyro torque ( $\tau_{gyro}$ ) is stabilization torque ( $\tau_{stab}$ ), but a component is generated in the yaw axis of the yacht as yaw torque ( $\tau_{yaw}$ ). The question often asked is 'does this effect the steering of the vessel?'. The answer is that the effect is insignificant, since the damping and inertia of the yawing axis is much much higher than in the rolling axis. In fact, by stabilizing the rolling motion, the vessel actually tracks much better in waves. Most vessels will yaw somewhat due to rolling motion as the changing waterplane shape causes the hull to turn as the roll angle changes. This is part of reason that fitting a gyro improves overall hull efficiency.



$$\tau_{stab} = \tau_{gyro} \times \sin \alpha$$

$$\tau_{yaw} = \tau_{gyro} \times \cos \alpha$$

...by stabilizing the rolling motion, the vessel actually tracks much better in waves...

## Calculating the Stabilizing Torque Delivered

Before we get into the details of how gyro-dynamics works, let's consider the basics and give you a straight forward way of calculating what a given gyro stabiliser can deliver in terms of stabilizing torque. Just like fins or tanks, gyro stabilizers produce a torque that opposes the rolling motion. It is the torque that does the work, so this is the primary statistic of interest. What may not be as obvious is that any time lag between the wave-induced rolling motion and the stabilization systems response reduces the effect of this torque.

Although difficult to understand at first, the basic math is really simple. The stabilization torque is equal to the angular momentum multiplied by the precession rate, multiplied by the cosine of the precession angle. This is true for vertical spin axis gyros (like VEEM Gyro) and also for horizontal spin axis gyros.

Angular Momentum [N.m.s] = Rotational Inertia of Flywheel [kg.m<sup>2</sup>] x Spin Speed [radians/second]

So now we have to calculate the inputs to these equations.

### Calculating Angular Momentum

Angular momentum is denoted  $K$  in this article. It has units of *Newton.metre.seconds* or N.m.s. For large gyros like VEEM Gyros this is sometimes reported as 1000 units of N.m.s or *kilo.Newton.metre.seconds* (kN.m.s).

Angular Momentum [N.m.s] = Flywheel Inertia [kg.m<sup>2</sup>] x Spin Speed [radians/second]

$$K = J_s \times \omega_s \quad [\text{N.m.s}]$$

Flywheel inertia is more specifically the polar moment of inertia of the flywheel about the spinning axis. We denote this figure as  $J_s$  (the 's' is for spin axis). The larger the mass of the flywheel, and the more this mass is distributed towards the rim of the flywheel, the greater the rotational inertia.

The spin speed (otherwise called the RPM), is simply the number of revolutions per minute that a flywheel completes. For the equations above this must be stated in units of radians/second, but the meaning is the same as rpm. To get from rpm to radians/second, use the following: Radians/second = RPM x (pi/30)

### Calculating Precession Rate

Here we will assume that the precession motion is proportional to the vessels rolling motion and is therefore roughly sinusoidal in nature.

Max Precession Rate = Precession Range x Frequency of Oscillating Precession Motion

The frequency of precession motion is equal to the rolling period of the yacht, so

$$\omega_{prec,max} = \dot{\alpha}_{max} = \alpha_{range} \times \omega_{roll} \quad [\text{radians/second}]$$

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$$\omega_{roll} = \frac{2 \times \pi i}{T_n} , \quad \text{where } T_n \text{ is the vessel natural roll period in seconds.}$$

## Calculating Gyro Torque and Stabilizing Torque

The gyro torque is the product of the flywheel angular momentum and the precession rate as below. The gyro torque acts in the plane of the spinning axis and the precession axis. Therefore, when the precession angle is away from vertical, the gyro torque can be resolved into a torque acting directly in the roll axis (the stabilizing torque), and an unuseful torque acting in the vessel yaw axis. Fortunately, the inertia and damping of marine vessels in the yaw axis is many times larger than the roll axis so this unuseful torque component has no negative effects. In addition, the yaw component of the gyro torque is approaching zero as the precession angle increases towards it's maximum. This is because in order to stop precessing at it's maximum range, the precession must decelerate and approach zero rate as it approaches maximum travel. At the maximum precession angle, the gyro torque is zero, and so is the yaw component. The combination of the diminishing amplitude of the gyro torque as precession angle approaches its maximum, and limiting the precession range to +/- 70°, results in the majority of the gyro torque acting to produce stabilizing torque, while the unuseful yaw component is comparatively small.

Gyro Torque [Nm] = Angular Momentum [N.m.s] x Precession Rate [radians/second]

$$\tau_{gyro} = K \times \omega_p$$

Stabilization Torque [Nm] = Gyro Torque [Nm] x SINE(Precision Angle) [nil units]

$$\tau_{stab} = \tau_{gyro} \times \sin(\alpha_{prec}) \quad [\text{Nm}]$$

## ...What next?

The following sections describe two tools that can assist you to understand what configuration of VEEM Gyro(s) is most appropriate for your yacht.

## GyroSize<sup>superyacht</sup>

### *GyroSize - Online gyro sizing calculator*

GyroSize is an online calculator that provides a detailed PDF report describing the VEEM Gyro installation options suitable for your yacht based on simple vessel characteristics.

The vessel data required to run a GyroSize calculation is:

- BWL (maximum waterline beam )
- Vessel Displacement (Full or Half Load Intact Condition)
- GMt (transverse metacentric height)

All of this data is available in the yachts Stability Booklet, located on the bridge.

Gyro stabilizer installations suited to the following Operational Profile options will be presented for your review and selection:

Operational Profile	Sea State	Waves up to
Profile 1 – Sheltered Water	2	0.5 m
Profile 2 – Coastal Water	3	1.25 m
Profile 3 - Open Water	4	2.5 m
Profile 4 - Blue Water / Ocean Explorer	5	Rough

Choosing the Operational Profile that most accurately reflects your intended yacht usage will ensure that the gyro installation selected will provide you with a level of stabilization that matches your expectations. If you are unsure, please speak to VEEM or your local VEEM agent to discuss the most suitable profile for you.

Access tool at [www.veemgyro.com/gyro-size/](http://www.veemgyro.com/gyro-size/)

Or by simply clicking on this button on our website:

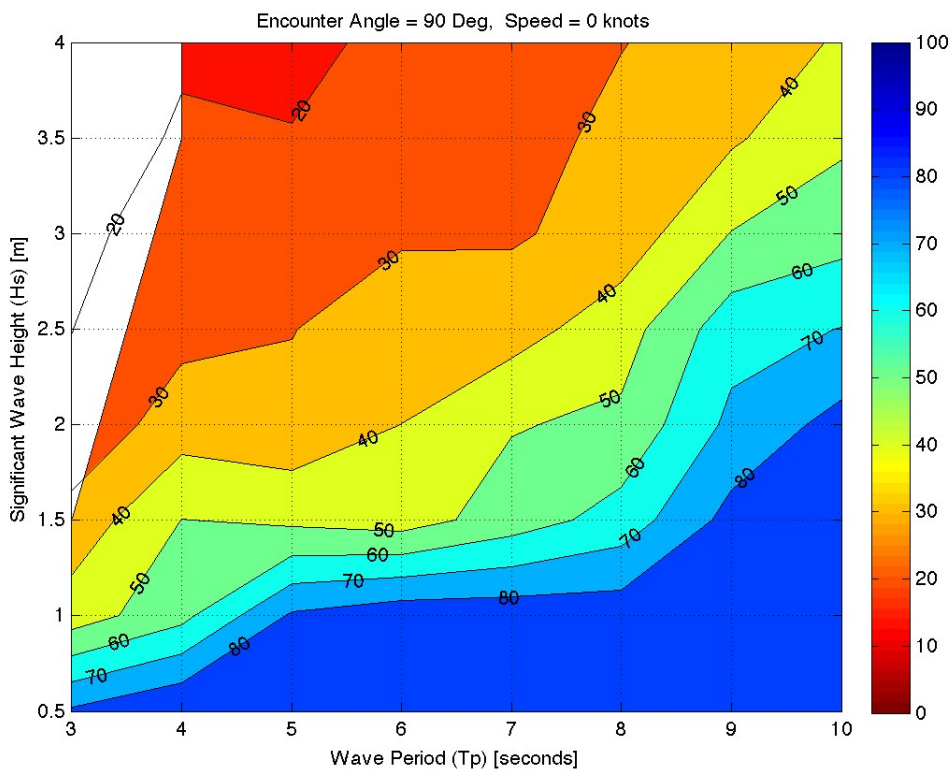


## GyroSIM – Detailed Time Domain Simulation

Once you have accessed the GyroSize online calculator and decided what VEEM Gyro stabilizer configuration(s) best suit your yacht, speak to VEEM about a detailed numerical analysis using our GyroSIM software. This analysis will tell you exactly how much roll reduction you can expect for a wide range of possible wave conditions.

VEEM's *GyroSIM* software is a detailed time domain simulation that takes as input a realistic irregular (random) seaway based on known mathematical representations. It considers the actual active precession controller used on the VEEM Gyro units, and accurately simulates the motion of the vessel in random realistic waves with the gyro switched off and with the gyro switched on. The result of a large number of rigorous time domain simulations is presented in a very informative color contour plot that gives the % roll angle reduction at a large number of wave height and wave period combinations.

A sample graphical performance chart is presented below.



This chart displays % roll reduction (%RR) as the contours (see legend in % to right). The percentage roll reduction (%RR) is the percentage reduction in RMS roll angle that is expected when the Gyro is turned ON. To use the chart, simply select a wave height and wave period combination and read off the predicted %roll reduction from the contour.

Request a GyroSIM simulation report at [www.veemgyro.com/enquiries/](http://www.veemgyro.com/enquiries/)