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Marine motion analytics

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Background

A Mobile Offshore Drilling Unit (MODU) is equipped with numerous pieces of machinery during its construction. This includes hoisting, rotating, and moving equipment designed to operate within manufacturer-specified structural limits. The structural limits are influenced by dynamic load cases; these are dependent on the environmental conditions and the vessel response and motion accordingly. Wave heights and wave periods will result in dynamic accelerations, impacting the equipment, due to the vessel's Response Amplitude Operators (RAOs). This table of wave heights and period specific to the equipment and location would then be used to determine if the equipment can be operated based on current sea state conditions. There are several errors (modeling and user) and inefficiencies associated with the above method.
There have been documented cases of operational activities and events, where rig personnel could not determine he additional dynamic loading exerted on equipment and rig structures, resulting in loads will exceeding the structural limtation of equipment or vessel structures. Samples of such offshore activities are as follows:

- Blow out Preventer (BOP) deployment/retrieval using the BOP transporter
- BOP and marine riser hang off.
- Well head tree deployment using the tree deployment carts
- Marine riser pick up with the vessel poedestal cranes or overhead cranes
- Open hole drilling with Top drives and deployment of surface conductor and casing
- General crane activties on the vessel.
- In field and extended vessel tows and mobilization.

The above are samples of activities that are dependent on the environmental sea states. Harsh environments or high Sea states could result in sever dynamic loading exceeding the vessels structural design limits.
This paper provides a pragmatic, accurate and clear method of determining if the current vessel dynamics are within the equipment operating specification without inference, removing the subjectivity and guess work.

Introduction

One of the significant issues that offshore teams encounter is determing the enviroments and the sea states associated with their respective operations. To an extent several weather forecasting services are utilized at periodic frequencies to estimate the weather criteria on drilling locations. Several vessels have also implemented weather monitoring equipment; however, these impose a high capital investment cost and have their limitations due to the vessel geometry and the respective offshore application.

Hence the most common practice is the use of the forecasted weather models daily to predict prevailing environments to determine the course of operational activities offshore. Which has proven difficult and unreliable at certain extremes, resulting in decisions based on the operator's personal judgement.

When a MODU is designed and constructed, a significant amount of modeling is done around the vessel's response to the environment. That environment is the effect of wind, waves, and current on the vessel's motions. More specifically, vessel motions consist of 6 degrees of freedom (6DOF) , 3 rotations, and 3 translations as shown in **Figure 1** below. These motions are referred to a ship-based coordinate system typically with an origin that coincides with the center of gravity of the vessel or C.G or center of rotation.

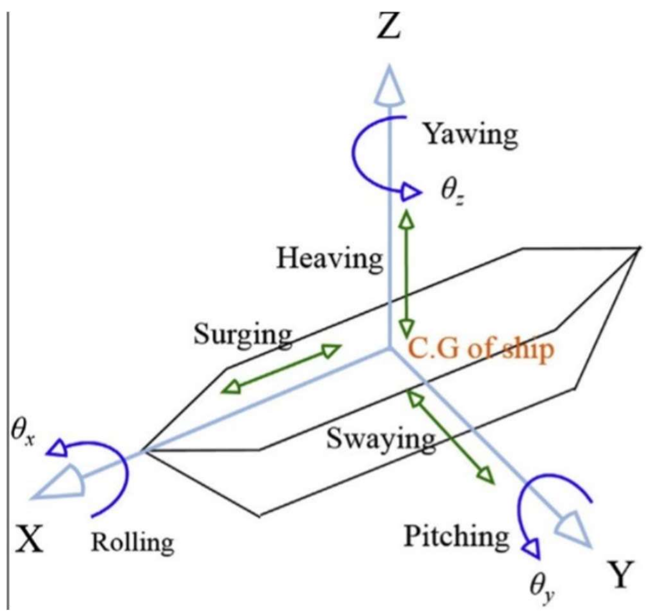

Figure 1: Illustration of 6DOFs for a MODU

In Transocean, we currently focus on two types of MODUs. The first is the Drill Ship with implied, ship shaped hulls. These have a more pronounced surge, sway characteristics in waves due to their shape. Secondly, Semi submersibles with larger diameter columns and deeper draft usually, these vessels are more stable, with lower heave and pitch response. In either case, however, both these hull types must be designed to handle severe environments. These requirements are driven by IMO MODU code and Classification society rules (DNV/ABS).

The design of these vessels are analyzed for normal operations, survival conditions and transit conditions during severe storm environments.

During the design, the vessel owner would typically specify the operating requirements of the vessel in terms of wind, wave height, wave period and current conditions required to be met for the specific region of operation . An example of such environment is indicated in Fig 2 below

Parameter	Operating Condition Intact Condition
Significant Wave Height, m (ft)	8.53 (28.0)
Wave Period Tp (s)	13.0
Wind (10mins), Kts (m/s)	60.0 (30.9)
Current Speed, Kts (m/s)	1.94 (1.0)

Figure 2

Ocean waves are the primary contributor to dynamic vessel motions. They cause a time varying force on the hull resulting in an oscillatory response in the 6 DOFs. The waves characteristics are typically described by two parameters:

Significant Wave Height (Hs) and;
Wave Peak Period (Tp)

It is important in the context of this paper to understand that Significant Wave height is s defined as the statistical mean *wave height* (trough to crest) of the highest third of the waves , for a given sea state. So, for Hs = 4m that would mean the maximum wave that may be seen could be 2 to 3 times or even more in a storm. Equally important is the wave period which is effectively the wave's energy spectrum. A sea state with a moderate wave height, but a critical wave period that resonates with the natural periods of the vessel can yield larger motions than a higher wave height with lower wave periods. The wave direction of course also plays a role in the vessel's motion.

General wind and current, unlike waves typically impose steady load forces on the vessel. It is the waves that induce short-term dynamic vessel responses. However, in combination with waves, wind can induce a slow drift oscillation as a second order effect on vessel motion, but these are typically small compared to just the wave forces.

The vessel response to the wave model is represented in a transfer function called a Response Amplitude Operation or RAO. The RAO is essentially the magnitude of vessel motion per unit of wave amplitude as a function of wave period and direction. So, for a fixed set of waves (height and period) applied to a vessel, the RAOs allows us to calculate how much the vessel will move in in each degree of freedom. As mentioned above, Semi Sub's are less sensitive to heave and as a result have small heave RAOs for operational sea states.

RAOs can be derived in two ways, using 3D modeling software such as ANSYS AQWA, WAMIT or SESAM HydroD, Or empirically through scale model testing. The standard RAO model is based on a linear wave response. The real behavior can include nonlinear effects (drag forces) or second order wave forces that cause slow drift, but RAOs give a good first approximation.

As noted these empirical methods, accompanied with estimated or forecasted wave heights and wave periods applied to RAOs in order to estimate 6DOF vessel motion has several error sources

- Original RAO model accuracy

- Interpolation of RAO table for specific wave height and period.
- Second order effects

A vessel, particularly a Mobile Offshore Drilling Unit (MODU), is equipped with numerous pieces of machinery during its construction. This includes hoisting, rotating, and moving equipment such as cranes, drawworks, top drives, rackers, and trolleys. Many of these large and critical pieces of equipment are designed to operate within specific allowable motion limits, minimizing the additional forces caused by the acceleration of the installed location. As part of the equipment specification, the manufacturer provides acceptable acceleration limits to the shipyard or organization responsible for constructing and installing the equipment. Based on the physical location on board, the shipyard or manufacturer then determines which wave heights and wave periods will produce accelerations within the equipment specifications using the vessel's Response Amplitude Operators (RAOs). This table of wave heights and periods specific to the equipment and location is then used to determine if the equipment can be operated based on current sea state conditions.

This is the current and commonly used process to determine if equipment can be used given a specific sea state. As mentioned above, there are several errors sources when using this approach. It is desirable to provide a system and method that can measure and assess accelerations experienced by the equipment to see if the conditions are within proper limits. We propose an alternative method to remove these unnecessary sources of errors and interpretation. To do this we directly measure the accelerations and rotation rates at a single location on the vessel.

Dynamically positioned MODUs have several acceleration and rotation rate measurement systems on board by design. They are known by several names, such as motion reference units (MRUs) or vertical reference units (VRUs) or inertial measurement units (IMUs) or inertial navigation systems (INSs). All systems have, for the purpose of this paper, an accelerometer and gyroscope triad. As we are discussing directly using the accelerations and rotation rates, we will use the more general term IMU.

It is important to consider the nature of acceleration measurements. Accelerometers measure the prior acceleration or rate of change of velocity of the IMU. These measurements are consistent of coordinate acceleration (movement in physical space) and the acceleration due to gravity as illustrated in Figure 3. So, for a perfect level and stationery IMU, you will see roughly 9.81 m/s^2 on your z (or vertical axis) accelerometer. Another item to be aware of with accelerometers is they have various noise and accuracy characteristics. So low grade IMUs (such as in a smart phone) will perform significantly differently than accelerometers used for navigation grade IMUs. Each IMU will typically have 3 accelerometers each orthogonal to each other to measure proper acceleration in X, Y and Z axes.

In addition to accelerometers, these IMUs have rate sensors that will measure the change in rotation angle around a single axis. Similar to accelerometers that also have accuracy and noise characteristics and are also mounted orthogonal to each other to measure rotation rates around the X, Y and Z axes.

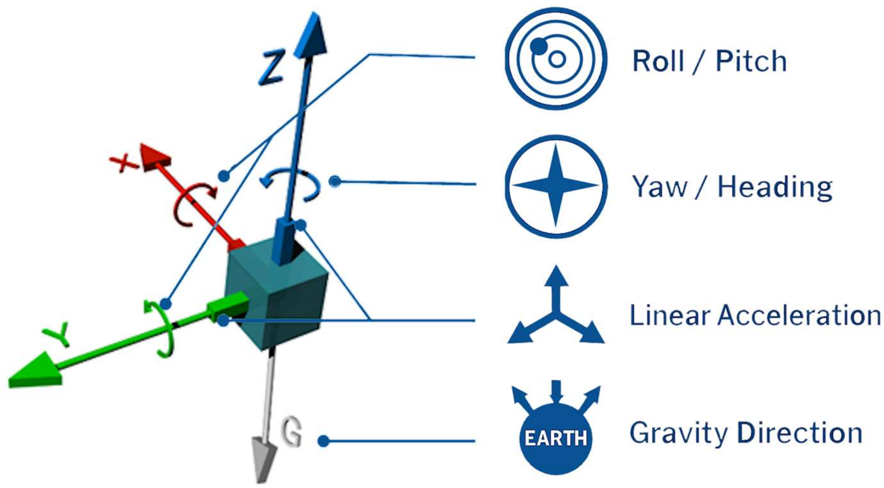

Figure 3: Illustration of sensor measurements for an IMU

The vast majority of IMUs are typically used as MRU/VRUs, and as such they are configured to output pitch, roll and possibly heave to the DP (Dynamic Positioning) system on board. They are not traditionally configured to output accelerations. So, when looking at capturing acceleration data from an IMU there are a few options

- Install a dedicated IMU for each location of interest
- Reconfigure the IMU/MRU/VRU used in DP to also output accelerations.
- Purchase a dedicated IMU and calculate the accelerations for each location of interest on the platform.

The following section will describe the method and equations used to simulate and then calculate the point accelerations for the equipment locations on the vessel.

SIMULATION

As we currently do not have access to logged acceleration and rotation rate data for our existing MRUs, however we can simulate the IMU acceleration and rotation data for algorithm validation. This was done by using an opensource IMU simulation tool published on GitHub and developed by Aceinna, a Massachusetts who's a manufacturer and supplier of MEMS IMUs. The simulation was based on medium grade IMU, not-Aceinna, qualified for Maritime use with the following key characteristics:

Gyro ARW:	0.3 °/√hr
Gyro Bias Stability:	3.5 °/hr
Accel Bias:	0.02943 m/s^2
Accel VRW:	0.00012 m/s/√hr

Then we defined the simulated rig motion focusing on station keeping in a relatively benign environment.

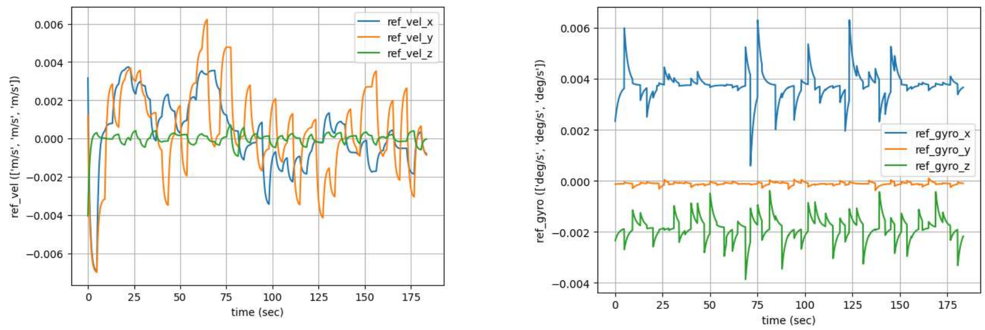

Figure 4:Input dynamics for simulated Rig motions

We then simulate the accelerometer and gyroscope data for all 3 axes based on the noise and accuracy characteristics for the simulated IMU.

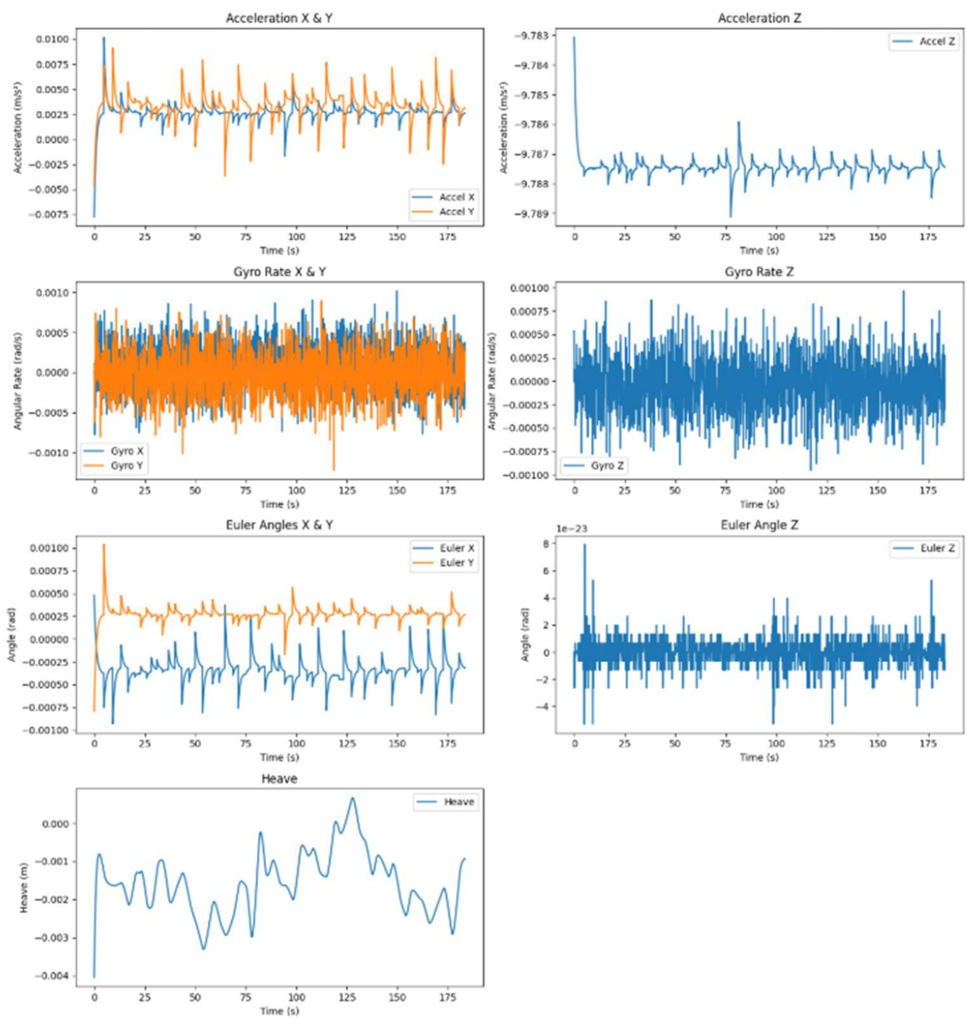

Figure 5: Simulated IMU Motion components

As you can see from the simulated accelerometer data in Figure 5 above, it is apparent that the gravity component is present in the accelerometer data. There are two options to remove gravity from the observations, so we get coordinated accelerations

- Select and IMU that provides an option to output the coordinate accelerations with gravity removed
- Remove it yourself algorithmically.

We prefer the first option above, however for the purposes of this paper we will work to remove gravity for completeness, so it is not limited to only IMUs with gravity removal capability.

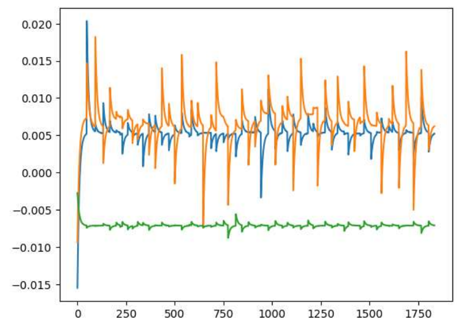

Figure 6: Simplified removal of heave component

There are several algorithms to accomplish this. Our simplified approach produces results that are similar; however, as shown in Figure 6 and compared to Figure 4 *ref_vel_z*, a notable bias remains. If removing gravity is managed outside the IMU further work to do this more accurately would need to be done. As removing gravity is not the focus of this paper and there are many published methods on how to do this and hardware solutions to accomplish same are available, we will not further devel into attempting to remove the remaining errors in Z accelerations. It can be further improved with a high pass filter, Kalman or complimentary filter.

Now to calculate the equipment locations based on accelerations and rotation rates measured at another point, we will use the following equation to begin. Subscript B indicated and measurement at the equipment location. Subscript I indicate a measurement at the inertial unit. Subscript BI indicates relative vectors from equipment to inertial unit.

$$\mathbf{a}_B = \mathbf{a}_I + \boldsymbol{\alpha} \times \mathbf{r}_{BI} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_{BI})$$

Equation 1

The component Euclidean vectors identified in Equation 1 are detailed in Equations 2a to 2d

$$\mathbf{r}_{BI} = \begin{bmatrix} x_{BI} \\ y_{BI} \\ z_{BI} \end{bmatrix} \qquad \mathbf{a}_I = \begin{bmatrix} a_{Ix} \\ a_{Iy} \\ a_{Iz} \end{bmatrix}, \quad \mathbf{a}_B = \begin{bmatrix} a_{Bx} \\ a_{By} \\ a_{Bz} \end{bmatrix} \qquad \boldsymbol{\omega} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \qquad \boldsymbol{\alpha} = \begin{bmatrix} \alpha_x \\ \alpha_y \\ \alpha_z \end{bmatrix}$$

Equation 2a: Position vector of point B relative to point I

Equation 2b: Acceleration at points I and B

Equation 2c: Rotational velocity component at I

Equation 2d: Rotational acceleration components at I

Expanding Equation 1 with Equation 2 components gives

$$\mathbf{a}_B = \begin{bmatrix} a_{Ix} \\ a_{Iy} \\ a_{Iz} \end{bmatrix} + \begin{bmatrix} \alpha_y z_{BI} - \alpha_z y_{BI} \\ \alpha_z x_{BI} - \alpha_x z_{BI} \\ \alpha_x y_{BI} - \alpha_y x_{BI} \end{bmatrix} + \begin{bmatrix} \omega_y(\omega_z x_{BI} - \omega_x z_{BI}) - \omega_z(\omega_x y_{BI} - \omega_y x_{BI}) \\ \omega_z(\omega_x y_{BI} - \omega_y x_{BI}) - \omega_x(\omega_y z_{BI} - \omega_z y_{BI}) \\ \omega_x(\omega_y z_{BI} - \omega_z y_{BI}) - \omega_y(\omega_z x_{BI} - \omega_x z_{BI}) \end{bmatrix}$$

Equation 3: Expanded body accelerations calc.

The equipment, IMU and the vessel are assumed to be of a rigid body system and there is no relative translational movement between them. In other words, the hull is assumed to have no significant flex. As such to determine the acceleration of the remote point B, it has two primary components, the linear acceleration of point I and the linear acceleration (Equ 2d) due to rotational velocity (Equ 2c) and accelerations of B around I. The IMU measures angular velocity not angular acceleration. As a result, there are two approaches used for the angular velocity component

- Set the angular acceleration component to zero as a second order effect on magnitude of resultant accelerations.
- Compute the angular acceleration using the time derivative (gradient) of angular velocity. This would be done to improve the accuracy and if we have high frequency IMU data to reduce numerical differentiation errors. The caveat is the differentiation will amplify noise and will require a low pass or Kalman filter to smooth the noise in the data.

Adjusted Equation 1, would now be

$$\mathbf{a}_B = \mathbf{a}_I + \frac{d\boldsymbol{\omega}}{dt} \times \mathbf{r}_{BI} + \boldsymbol{\omega} \times (\boldsymbol{\omega} \times \mathbf{r}_{BI})$$

Equation 4 : Body acceleration , dynamic calc

As we are targeting at least 10hz data, with respect to large vessels this could be considered sufficiently sample rate for the calculation. In our example we will skip the step for filtering the angular data for simplicity.

For a 5-meter lever arm offset and the simulated vessel dynamics, the resultant accelerations are shown in Figure 7.

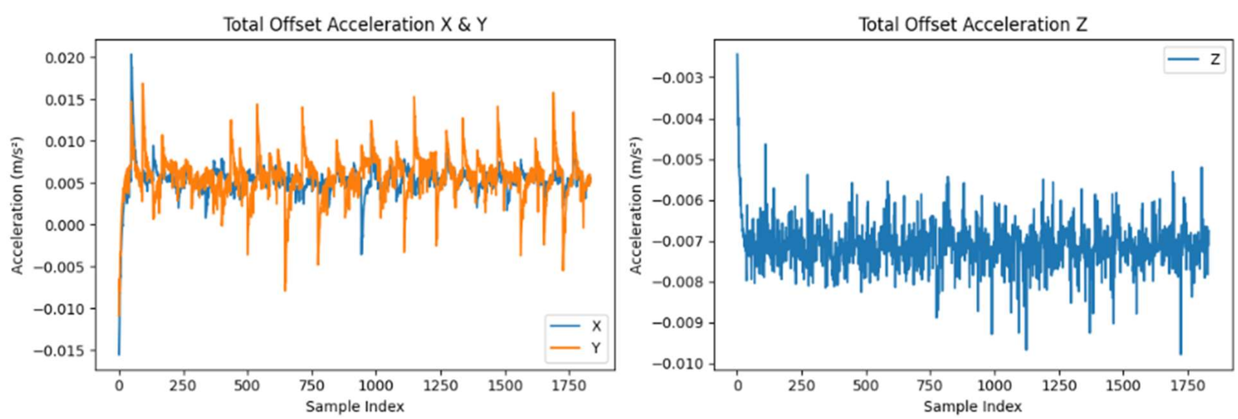

Figure 7; Body acceleration for offset location

The interesting thing about the next step is that we no longer need the RAOs, we no longer need a table of wave periods and heights to determine if a piece of equipment can operate in the current environment. We would just need the equipment point acceleration limits.

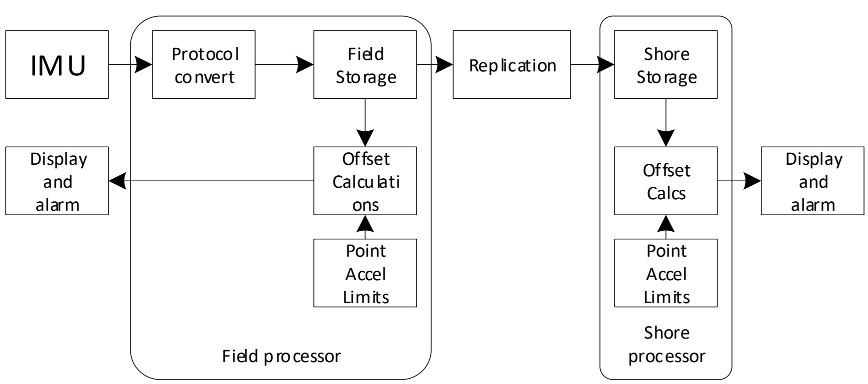

Figure 8: Simplified data flow

Figure 8 above illustrates a simplified data flow for this application, supporting both vessel operations and remote monitoring from shore. The IMU outputs data to the controller which will then always monitor accelerations or at specifically directed times, such as when the piece of equipment is desired to be operated. The offset location of the equipment from the IMU is applied using the algorithm described above to determine the point accelerations and compare those to the provided point acceleration limits. It can be further integrated with a safety system if the motions exceed the limits, by sending a signal to the equipment to halt operation. This is then displayed and if limits were exceeded, alarms are triggered for the operator on board. The data can also be replicated to shore as shown above for monitoring and performing the same calculation, display and alarm functionality for shore-based supervisors.

Conclusion

The paper provides a method to accurately and clearly determine if the current vessel dynamics are withing the equipment operating specifications without inference, subjectivity or guess work. In our examples above, it is focused on MODUs. However, it can be equivalently applied to any marine platform or ship equipment. It removed the need for look-up tables and is a direct measurement of equipment motion.

References

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- International Maritime Organization, *International Code on Intact Stability*. London, UK: IMO, 2008.
- Aceinna, “gnss-ins-sim,” GitHub repository. [Online]. https://github.com/Aceinna/gnss-ins-sim. [Accessed: Jan. 15, 2026].