SpinTransit Participant Study

R. J. Hartman, Ph.D., SeaSoft Systems
D. W. Smith, Ph.D., ExxonMobil Upstream Integrated Solutions Company

Abstract

In December 2019, SeaSoft® Systems, working in collaboration with ExxonMobil Upstream Integrated Solutions Company (EMUISC), organized a multi-participant study of the transient behavior of a highly idealized vessel and mooring system dubbed SpinMoor™: a turret-moored tanker subject to a constant lateral force applied at midships. The SpinMoor Participant Study report [1] noted that amongst a universe of 10 independent commercially available time-domain mooring programs capable of simulating SpinMoor, there existed a variability of order 100% (a factor of 2) in predicted offsets and turret loads, with estimates falling into two groups, one at each end of that range, and with an equal number of submissions in each group. The report concluded that, due to the simplicity of the system and environment, and the systematic elimination of all user-controllable parameter adjustments, the differences could only be explained by "flaws in the underlying time-step numerical algorithms, or the implementation of the underlying dynamical laws, or both, for a significant subset of the ten participating codes."

To further explore possible sources of the SpinMoor participant bifurcation, a follow-on study was organized to simulate a system of even greater simplicity, comprising the SpinMoor tanker, underway in an ideal inviscid fluid, without mooring restraints or forcing agents of any kind beyond hydrodynamic reactions associated with motion in an ideal fluid. This 'Gedanken-experiment' imagines vessel motion comprising simultaneous rotation and translation: hence, a "SpinTransit™".

All software vendors contributing to the 10 independent SpinMoor submissions were invited to join the SpinTransit study; two declined to participate, and one new program was added, resulting in 9 independent SpinTransit solution submissions.

The simplicity of the SpinTransit protocol would suggest that all comprehensively vetted vessel motion simulations should, within limits determined by floating-point numerical accuracy, reproduce the closed-form SpinTransit solution first published well over a century ago [2]. Yet, the SpinTransit study documents greater variability than the SpinMoor report, with the 9 SpinTransit results falling into three qualitatively distinct groups, each group comprising 3 submissions. This trifurcation contrasts with the less complex, but equally problematic, bifurcated clustering documented in the SpinMoor report.

A detailed analysis of SpinTransit submissions points clearly away from numerical time-step algorithmic differences considered in the opening paragraph above, and reveals instead unequivocally flawed implementations of Newton's Laws in two thirds of the nine independent submissions. We designate and identify two broad classes of time-domain simulations represented in the SpinMoor and SpinTransit studies: Newtonian Compliant ("NC") and Newtonian Non-Compliant ("NNC").

1 The SpinTransit Study: Motivation and Historical Perspective

Motivation for the SpinTransit study derives from the surprising and problematic results of its predecessor: the SpinMoor study [1]. The historical impetus for the SpinMoor study is documented in considerable detail in the SpinMoor report and is only summarized briefly here. A careful review of the SpinMoor report [1] and its Appendices is a prerequisite to an in-depth understanding and appreciation of this sequel.

Spanning a period of several years, ExxonMobil affiliated companies noted a surprisingly large variability of system load and offset estimates for turret-moored FPSO systems subjected to transient wind squall conditions. These estimates were provided by multiple independently commissioned analysts, each relying on different commercially available simulation products. The SpinMoor study was organized to systematically quantify and probe the possible role of simulation software in these historical anomalies. The study revealed a level of variability between commercially available software offerings consistent with the anecdotal experiences in the historical design studies.

However, the SpinMoor study was insufficient to fully disentangle the relative importance of 3 possible contributors to the observed vendor differences: (A) differing values of "user adjustable parameters", (B) flaws in the underlying time-step numerical algorithms and (C) flaws in the implementation of the dynamical physical laws. The SpinMoor report addressed directly the possibility of inappropriate user controls (A), and demonstrated that misuse of such controls (system damping levels, for example) could produce without difficulty response differences comparable to those found in the historical record [1; Appendix V]. However, without additional information it was not possible to apportion the cause of the observed historical estimate differences between contributions from A, B and C above.

The particulars of the SpinMoor thought experiment were crafted by SeaSoft to permit a straightforward and unequivocal theoretical analysis that would provide rigorous arbitration should participant results show a high degree of variability. As the purpose for the study was to determine the veracity and reliability of historical simulation results used in the design of moored assets already deployed, there was no advance disclosure to SpinMoor participants of the existence of unequivocal theoretical results; this was to insure that participant submissions would not be influenced by a-priori knowledge of the correct behavior. Only by that mechanism could we reasonably hope to clarify the sources of differences found in the historic comparisons of mooring system performance produced by independent analysts.

2 The SpinMoor Aftermath

The SpinMoor report produced considerable discussion, and some controversy, in the offshore mooring community. An executive summary:

Roughly one-half of commercially available time-domain software offerings suitable for the SpinMoor study, carried out by the software vendors or experts designated by the vendors, failed to predict to within a factor of 2 (i) the correct peak or (ii) the steady-state mooring loads for a simplified dynamical system designed to characterize wind squall or current eddy events impacting a fully-loaded weather-vane capable vessel and mooring system.

The SpinMoor report was silent as to the correct theoretical response. This was necessary because we anticipated (as discussed in SpinMoor report Appendix III: "Alternate Testbeds"), that a follow-on study would likely be necessary to further clarify variability found in SpinMoor submissions. As noted at the end of sub-section 1 above, we believed that revealing the correct SpinMoor response in the SpinMoor report, or prior to analysis of additional comparative studies, would result in an effort on behalf of software developers to repair faults discovered in their products. Such repairs would compromise the "backwards-in-time" review of completed design projects that was the primary objective of our efforts.

The SpinMoor findings, including a careful analysis of both the transient and steady-state SpinMoor response predictions, confirmed the previously suspected belief that the dynamical modeling underlying more than half of the submissions in the SpinMoor study was fundamentally flawed. That is, the results are incompatible with Newton's laws of motion. We thus concluded that SpinMoor result variability does not result *solely* from (A) user input differences, or (B) a failure of the employed numerical methods to faithfully represent the correct underlying dynamical equations, but must involve (C) *incorrect formulations or implementations of Newton's Laws*.

Furthermore, the SpinMoor study did not point unequivocally to a *single* isolated theoretical modeling failure; rather there were, in the details of the transient behavior and other indications, hints that more than one modeling flaw was involved in SpinMoor submission differences. These circumstances argued strongly for a follow-on study to investigate how widespread might be the suspected failings in the theoretical underpinnings of many SpinMoor participants.

In addition to our internal analysis of the SpinMoor results, immediately following release of the study there occurred an extended email exchange amongst mooring experts regarding its findings. Included in that exchange was speculation, and considerable analysis, about which of the two groupings revealed in the report corresponded to the "correct" solution. This speculation failed to reach a consensus, with competing suggestions that (i) widespread incorrect assignment of added mass values, and/or (ii) the inclusion or exclusion of so-called "maneuvering loads," might be responsible for the study's bifurcation into "L" (large load/offset) and "S" (small load/offset) groups.

These collective circumstances pointed to a need for an investigation into the Newtonian methodology used in participant programs; this objective formed the impetus for SpinTransit. All participants of SpinMoor were invited to join the SpinTransit comparative study. See Appendix I for the SpinTransit protocol.

3 Requests for Intra-Study Simulation Repair and Revision

As noted in the April 28, 2020 SpinMoor "Revision 1" report, two participants were permitted to submit revised results for that release; quoting from the Revision 1 document:

Subsequent to the discovery of erroneous zero-frequency added mass values in their SpinMoor submissions, two participants submitted revised results. The report graphics and tables have been updated using the participant's corrected data [Ref 1; pp1].

We emphasize that these two participants presented satisfactory evidence (comprising portions of the input stream driving their simulations) that their original submission contained numerical errors resulting from confusion over the (admittedly peculiar) SpinMoor protocol units used for vessel zero-frequency added mass specifications. These errors produced, respectively, added mass values 1 and 2 orders of magnitude too small in the original submissions from those two participants.

Following release of the SpinTransit study invitation and protocol, two more SpinMoor participants requested to submit revised SpinMoor results, not because of numerical input errors of the kind described above, but in order to make changes to their simulation software based upon (i) review of their preliminary SpinTransit efforts; and/or (ii) information shared through the community discussions subsequent to the SpinMoor report noted above; and/or (iii) in at least one case, the discovery of the analytical solution to SpinTransit [2]. We responded to those two requests as follows:

> *The central goal of the SpinMoor and SpinTransit studies is to explore issues in widely-used commercial software that have impacted mooring simulations of importance to ExxonMobil subsidiaries in recent years. The studies were not intended solely to help vendors troubleshoot their software, although they will clearly be useful to all participants, and others, going forward.*
>
> *To achieve our goal of assessing the validity of mooring simulations done in the past, we need a meaningful snapshot of results produced by programs as they existed at the outset of the SpinMoor and*

SpinTransit studies. Please submit SpinTransit results produced by the same code base/software version number/build number as used in your SpinMoor submission.

Ultimately, two SpinMoor participants (including one but not both of the two mentioned just above) declined to participate in SpinTransit; their reasons are instructive:

One participant, after reviewing the widely disseminated (inconclusive) speculation about which of the two SpinMoor groupings represented the "correct" solution, declined to participate in SpinTransit, noting: "We expect that the results from the (SpinTransit) study will differ between the participants resulting in a discussion about what is correct and what is wrong."

The second SpinMoor contributor opting out of SpinTransit declined to enroll unless they were allowed to use a *different* version of their software for their SpinMoor and SpinTransit submissions, a request which we rejected. Prevention of real-time intra-study "simulation repair" has from the outset been a guiding principle for these comparative studies, in order to obtain meaningful insight into the validity of past design studies done for offshore assets already deployed and operational. The loss of these two participants' submissions, and the addition of one new submission, reduced the total number of datasets submitted from 10 (for SpinMoor) to 9 (for SpinTransit).

4 Study Design Considerations

To cast further light on mechanisms responsible for the SpinMoor bifurcation, we chose a minimal system, eliminating the moorings, dissipation, and all external forces and moments save those deriving from inertial hydrodynamic reactions with the surrounding fluid. The system is sufficiently simple that its temporal evolution can be determined by purely analytical means [2]. More interestingly, the SpinTransit time history can be established without any mathematics whatever, relying solely on long-established Newtonian conservation laws.

5 Protocol: Vessel, Environment and Initial Conditions

The SpinTransit vessel is identical to the Marin stock 200 kdwt tanker used in the SpinMoor study, unmoored and moving in an inviscid ocean. The protocol (Appendix I) contains details, including a discussion intended to assure correct inclusion of the "Munk moment" acting on a body moving in an ideal, inviscid fluid.

Initial conditions ($t = 0$) comprise a vessel tracking northwards (in the "X" direction) at 1 meter/second and rotating counterclockwise about its CG at a rate of 1 degree/second.

6 Grouping of Results

SpinTransit submissions exhibit considerably greater variability and complexity than those in the SpinMoor study, with three distinctive response sets, each set containing three submissions. Amongst submissions in each group, the results are so similar that in most cases individual submissions cannot be distinguished when plotted together, with plotted curves lying directly atop one another.

Group 1: Participants {1, 2, 3}
Group 2: Participants {4, 6, 8}
Group 3: Participants {5, 7, 9}

Vessel track visualizations and motion summaries, taken directly from tabular time histories for the 100% load case, can be found in Figures 1 through 6. Additional results for the 100% load case can be found in Appendix III. Complete data for the 40% load case (the "ballasted condition") are included in Appendix IV.

7 Newtonian Compliance of SpinMoor and SpinTransit Groups

The SpinMoor and SpinTransit studies now complete, we can identify the dynamically correct branches of each study as determined by purely theoretical analysis: Group "L" of SpinMoor and Group "1" of SpinTransit. A reminder: for the fully loaded vessel, the SpinMoor "L" group is associated with vessel offsets and mooring loads approximately 100% larger than the "S" group; this is well in excess of typical modern safety factors.

Interestingly, while *every* member of SpinTransit Group 1 belongs to SpinMoor Group "L", the converse relationship does not hold. That is, every member of SpinMoor Group "L" is *not* likewise a member of SpinTransit Group 1. Only the subset of participants present in *both* Group "L" of SpinMoor *and* Group 1 of SpinTransit receive an unqualified Newtonian Compliance ("NC") designation for our purposes. Of the two SpinMoor participants who declined to submit SpinTransit results (see subsection 3 above), one was a member of Group "L" (the analytically correct group) and the second was in Group "S".

8 Per-Participant Multiple Submissions

As in the SpinMoor study, participants were permitted to submit multiple solutions representing distinct underlying computational methodologies available in their simulations. In the SpinMoor study, 8 participants submitted a total of 10 solutions, (i.e., 6 participants submitted a single solution, and the remaining two participants submitted two solutions each). The SpinTransit submission universe comprises 9 independent solutions from 6 participants, with one participant submitting two solutions and a second participant (SeaSoft) submitting three solutions.

As documented in the SpinMoor report, SeaSoft contributed two SpinMoor submissions, produced by a time-domain adjunct ("Squallsim®") to SeaSoft's frequency-domain program offerings; those submissions comprised one member in each of the SpinMoor "L" and "S" Groups. Similarly, SeaSoft's three SpinTransit solutions are represented, one submission per group, in SpinTransit Groups 1, 2, and 3.

As discussed above (Section 7), only SpinTransit Group 1 submissions exhibit Newtonian Compliant (NC) results, so it is natural to ask why SeaSoft would expend the effort to develop Squallsim capabilities known to be Newtonian non-compliant (NNC), and to submit those solutions to SpinTransit Groups 2 and 3. This question was addressed briefly in the historical notes of the SpinMoor report, but we wish to review and expand that discussion in the SpinTransit context.

Squallsim's two independent NNC theoretical models have been developed over time, beginning with Squallsim's introduction in 2016, in order to facilitate and simplify comparisons with other established time-domain simulation products, and to provide a streamlined mechanism for evaluating the impact on earlier design studies prepared using possibly Newtonian non-compliant software tools. As an example, this comparative capacity was called upon to permit several comprehensive design study comparisons between the Squallsim NC and NNC options, as documented in considerable detail in SpinMoor Appendices VII – IX [1, 4]. Those seeking guidance as to the practical implications of NNC in operational circumstances should carefully review those appendices.

9 Group 1: Newtonian Compliant

SpinTransit Group 1 comprises all participants whose submissions faithfully reproduce the SpinTransit analytical solution [2]; we refer to these submissions as "Newtonian Compliant" (NC). Group 1 individual results are virtually indistinguishable; a single set of summary graphics and comments serves to characterize all three members collectively. Further, Group 1 submissions are uniquely identifiable by their strict compliance with Newtonian conservation of momentum (linear and angular) and energy, as discussed further below.

10 Groups 2 and 3: Newtonian Non-Compliant

The Newtonian non-compliant ("NNC") responses of SpinTransit Group 2 comprise three participants who were also members of SpinMoor's "S" Group.

The three NNC responses of SpinTransit Group 3 are the most diverse, comprising one member from each of SpinMoor Groups "L" and "S", and one additional SeaSoft (Squallsim) submission not included in the SpinMoor universe.

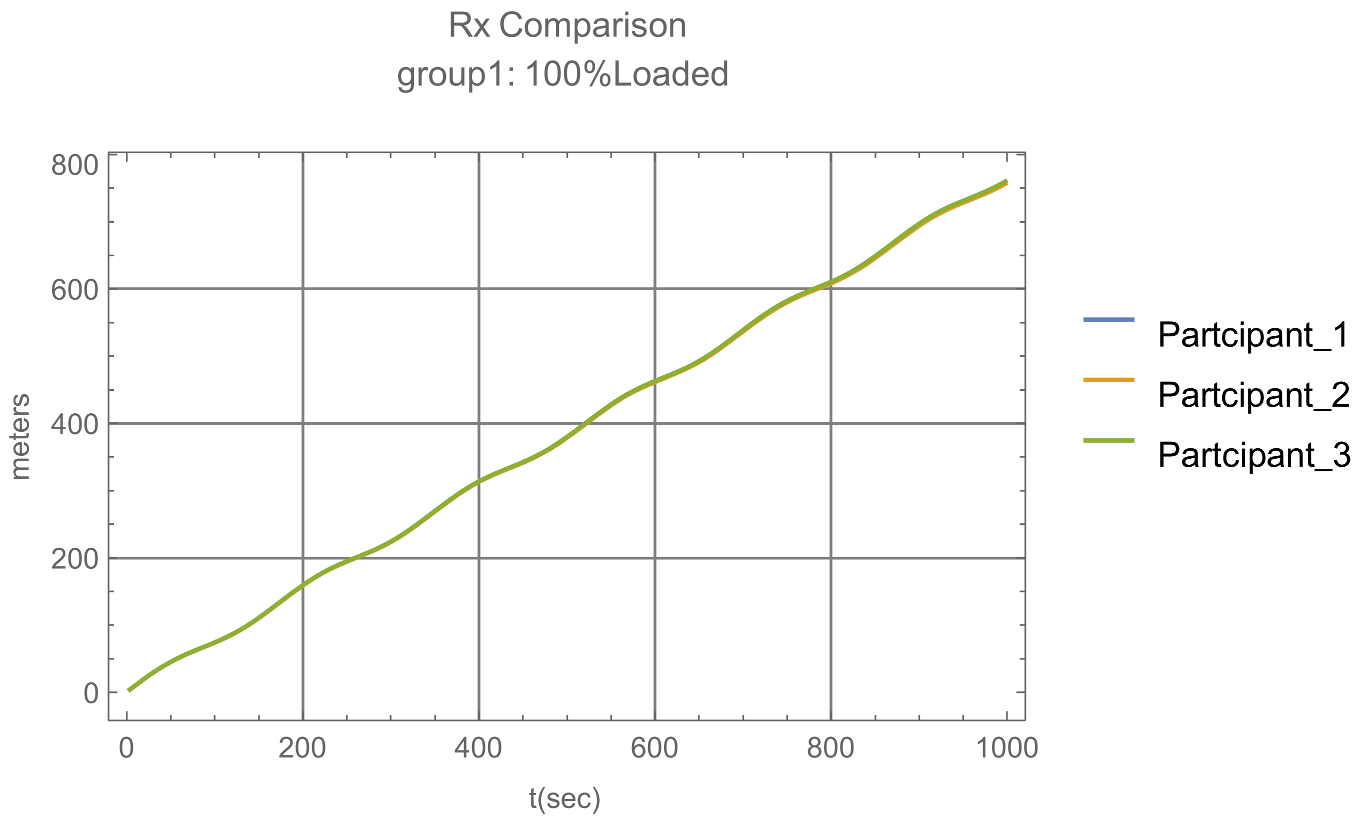
11 Graphical Summaries

The figures below contain graphical summaries of participant submissions for the 100 % loaded condition. Results for the 40% ballasted condition are highly similar qualitatively, add little of immediate interest, and can be found in Appendix IV.

The Group 1 graphics subset selected for display below is slightly more comprehensive than that of the other two groups, to highlight in greater detail their analytically defensible, Newtonian compliant, SpinTransit time histories.

Group 2 and 3 graphics are provided to visualize the nature and extent of the differences between the three groups. In all graphic displays, $\{Rx, Ry\}$ and $\{Vx, Vy\}$ refer to the instantaneous x and y coordinate and velocity components of the vessel CG; Rxy is the radial distance of the vessel CG from the origin of coordinates. Complete graphics for all participants are collected in Appendices III and IV.

Figure 1a. Newtonian Compliant Response Visualization: Group 1



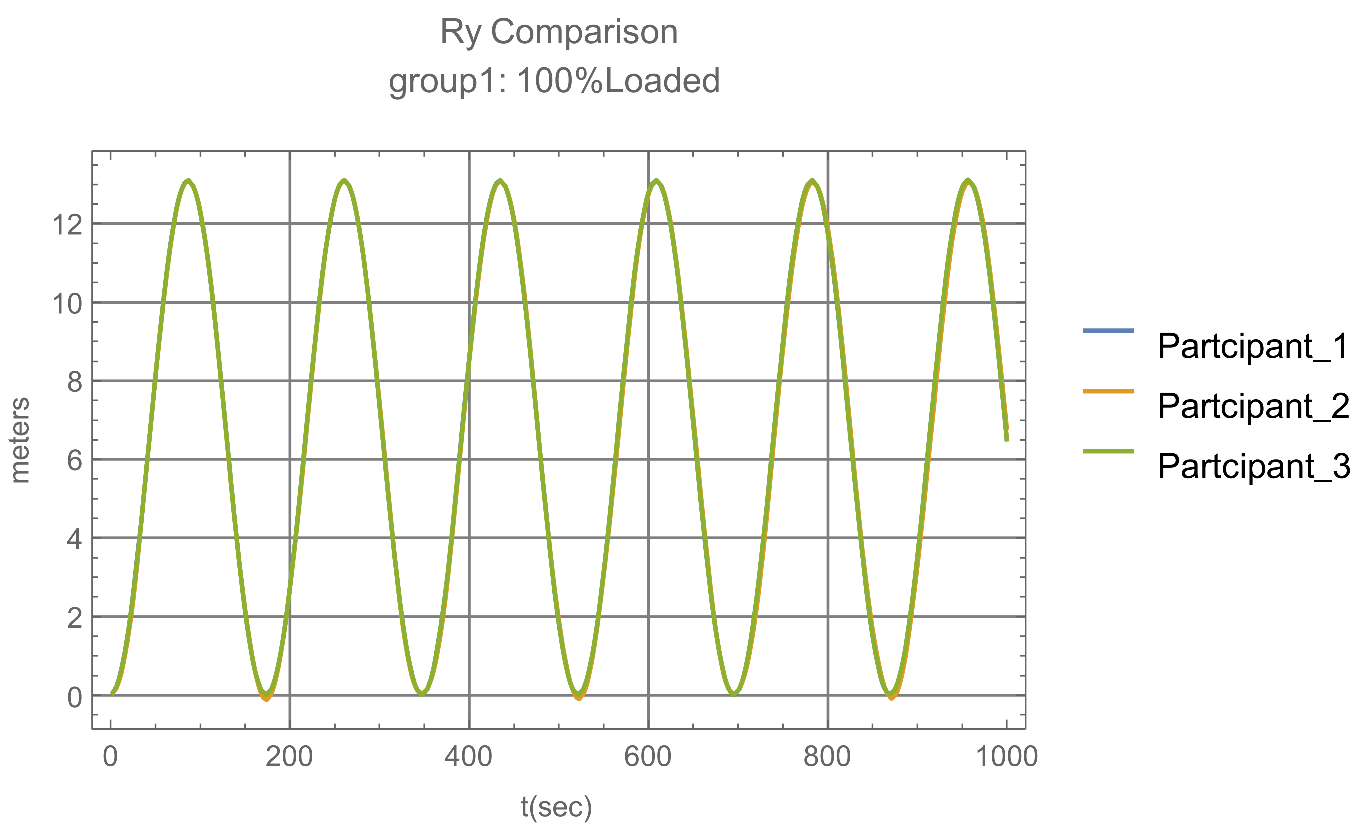
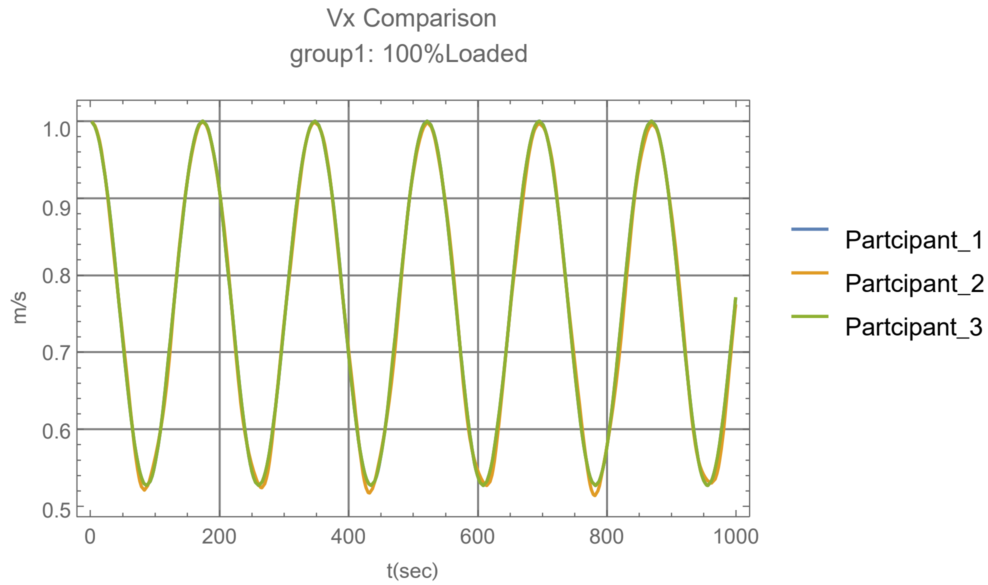
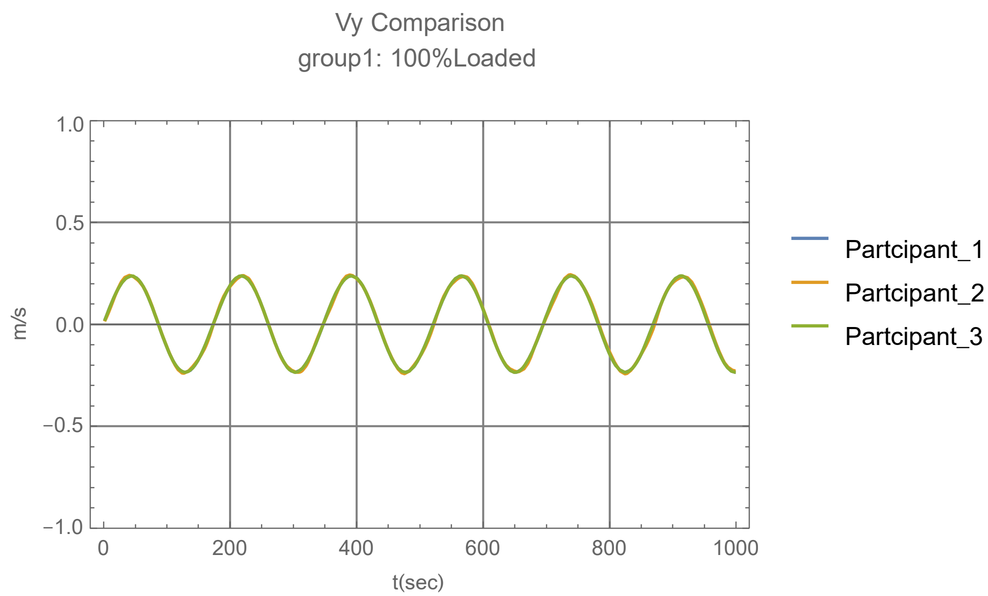


Figure 1b. Newtonian Compliant Response Visualization: Group 1





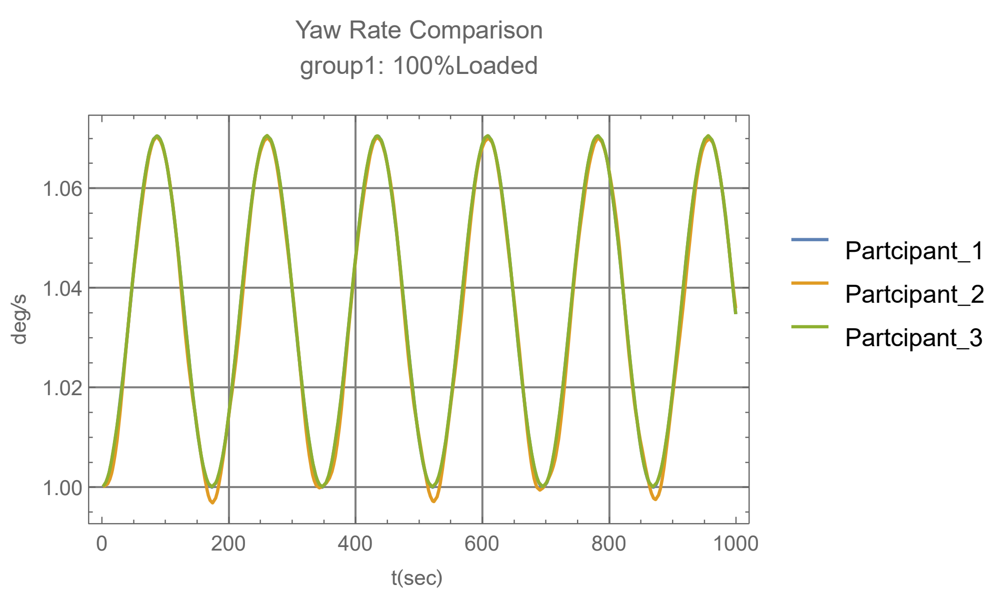
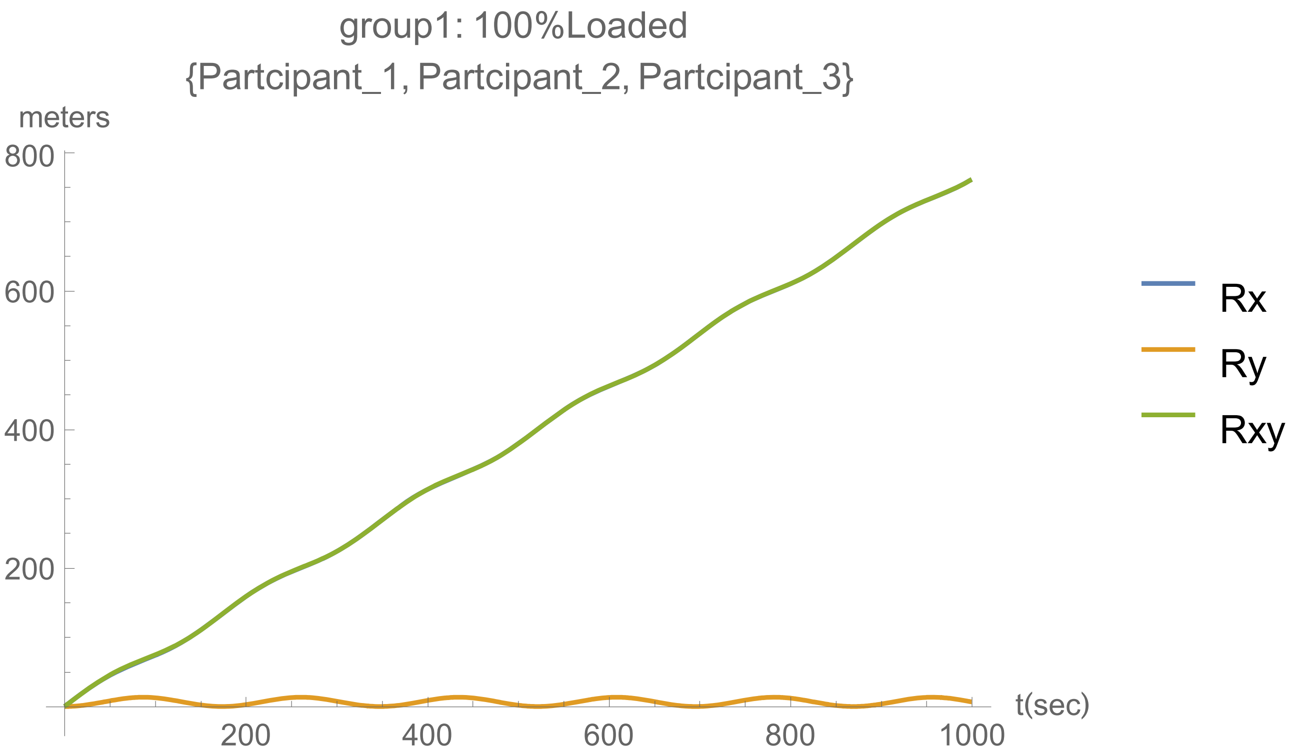
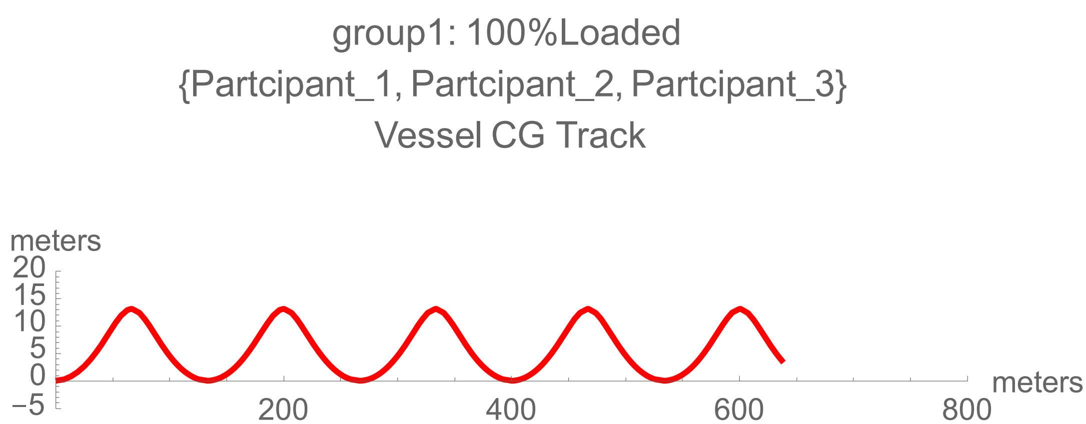


Figure 1c. Newtonian Compliant Response Visualization: Group 1





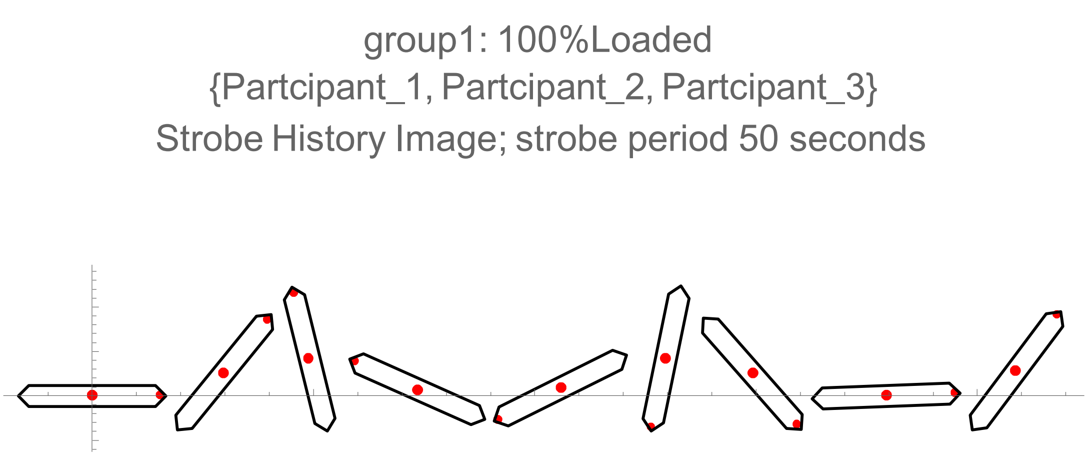
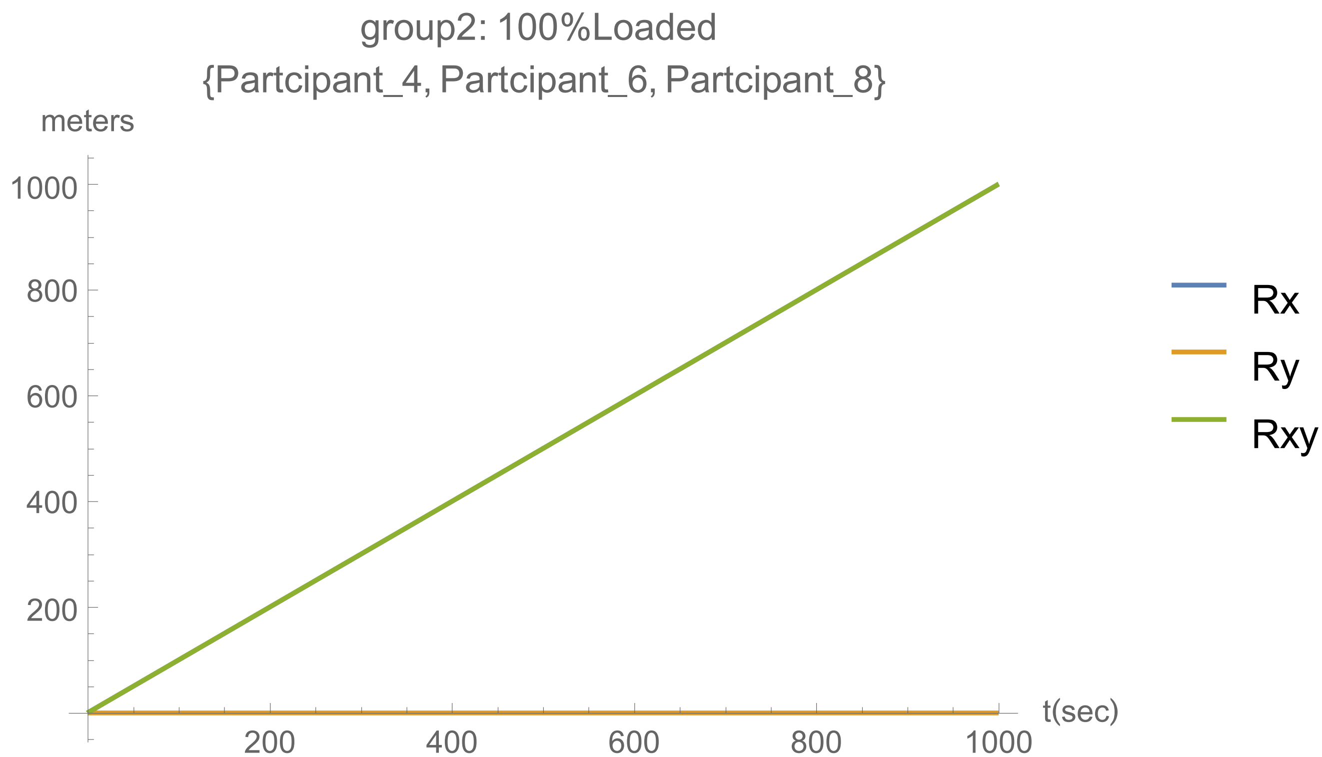
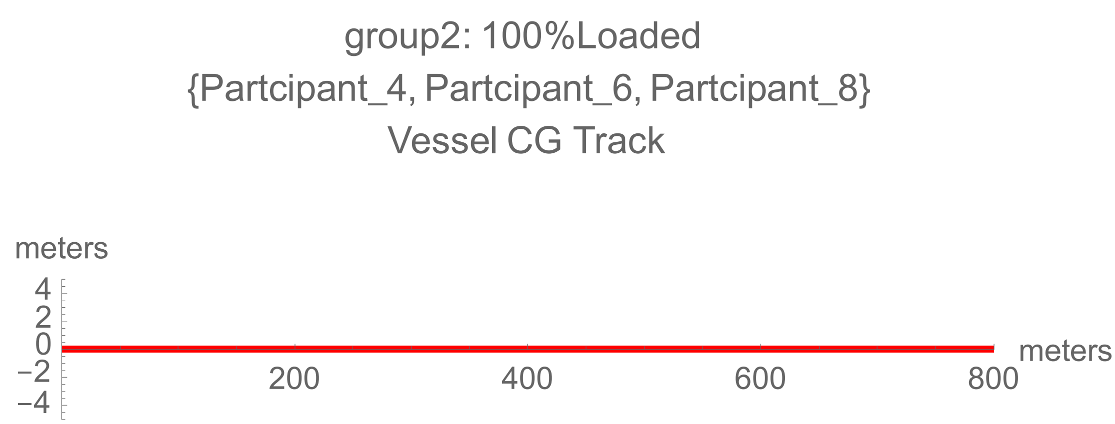


Figure 2. Newtonian Non-Compliant Response Visualization: Group 2





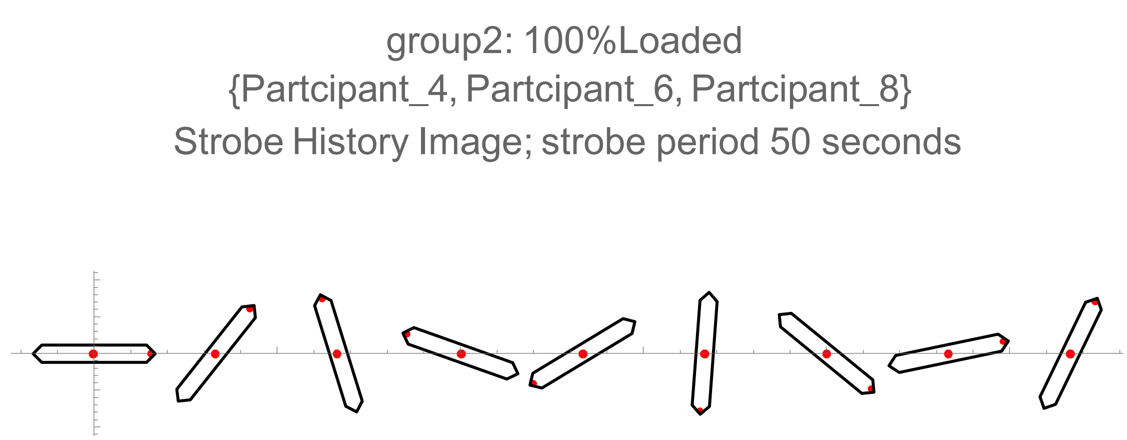
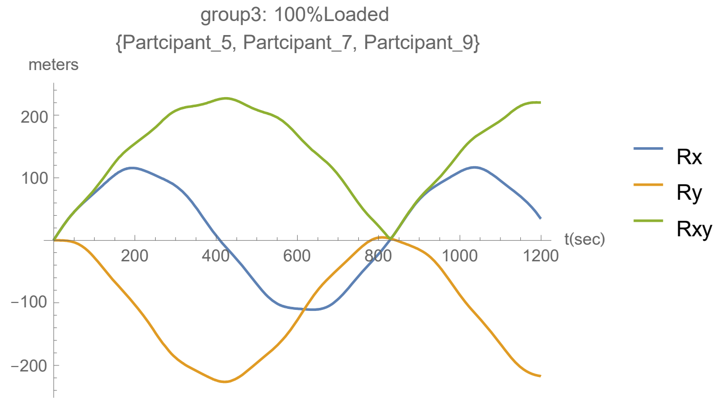
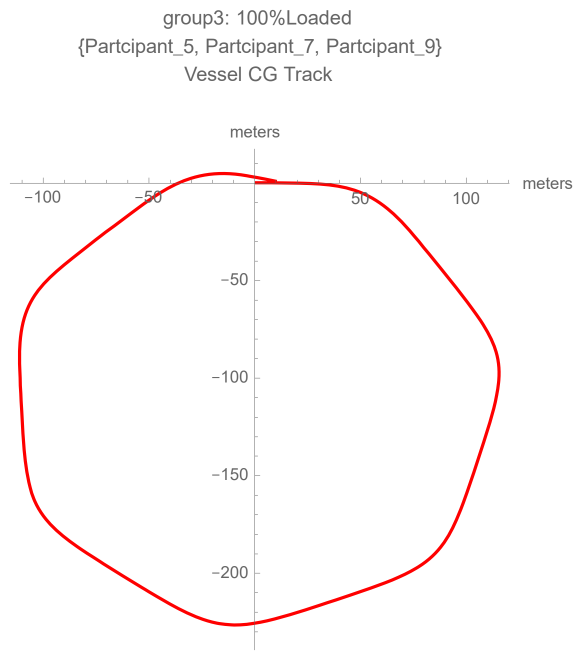
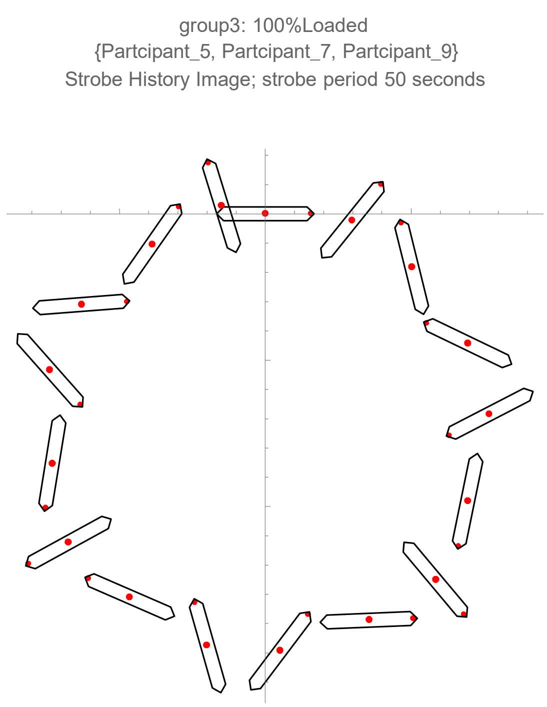


Figure 3. Newtonian Non-Compliant Response Visualization: Group 3







12 SpinTransit Newtonian Compliance Checks

The translation of Newton's Laws into computerized algorithms for complex mechanical systems is problematic; even the world's best and brightest engineers sometimes get it wrong, often with serious consequences [8].

In lieu of complicated mathematical arguments [2], we press into duty three unequivocal tests for Newtonian compliance: conservation of energy, linear momentum, and angular momentum. Any formulation of Newton's laws, regardless of system complexity, must in the end strictly conserve energy and momentum. The absence of dissipative mechanisms in the SpinTransit protocol offers us analytically trivial shortcuts to test for Newtonian compliance.

Initial Condition: $t = 0$

At $t = 0$, the vessel is set in motion; this motion is associated with a specified initial [vessel + fluid] linear $\{Px, Py\}$ and angular $\{L\}$ momentum, and kinetic energy $\{KE\}$: $\{Pxo, Pyo, Lo, KEo\}$. The initial linear momentum vector of the combined (vessel + fluid) system, resolved in global coordinates, $\{Pxo, Pyo\}$, has only a *Pxo* component, proportional to the initial vessel forward speed (1 m/second) and to the virtual mass, "*Mx*", of vessel + fluid in surge. *Mx* comprises the sum of the "drydock" vessel mass, plus the zero-frequency hydrodynamic added mass in surge. At $t = 0$ the sway velocity, and the associated *Pyo*, are both identically zero. The initial system angular momentum, "*Lo*", evaluated about a globally fixed vertical axis through the coordinate origin (the vessel CG at $t = 0$), is proportional to the initial yaw rate (1 degree/second), and to the virtual moment of inertia in yaw "*I*" (the sum of the "drydock" vessel moment of inertia and the zero-frequency hydrodynamic added moment of inertia for pure yaw rotation about the CG). The initial Kinetic Energy is the sum of its translational and rotational contributions at $t = 0$:

$$KEo = Pxo^2/(2*Mx) + Lo^2/(2*I).$$

Note that *L*, like *KE*, has *two* contributions in general: *Lrot* (angular momentum arising from vessel rotation about its CG), and *Ltrans* (angular momentum about the coordinate origin arising from translation of the vessel CG). The total angular momentum *Ltot*, the conserved quantity, is simply the sum of these two contributions. At $t = 0$, when the CG is at the coordinate origin, we therefore have:

$$Ltrans = 0,$$
$$Lo = Lrot(t = 0).$$

Subsequent Motion: $t > 0$

Newtonian momentum and energy conservation requires that, in the absence of external forces or moments applied to either vessel or fluid, all four quantities $\{Px, Py, L, KE\}$ remain constant at their initial $t = 0$ values. That is:

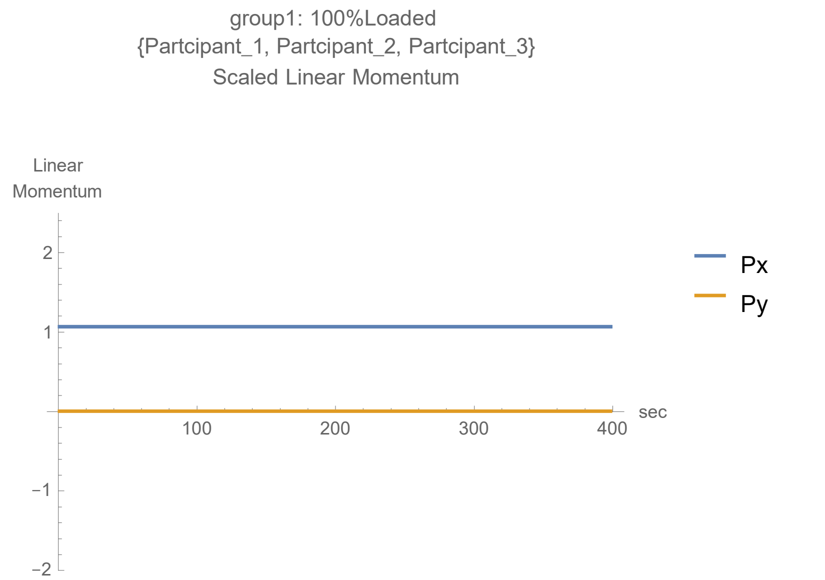
$$Px(t) = Pxo$$
$$Py(t) = Pyo = 0$$
$$Ltot(t) = Lrot(t) + Ltrans(t) = Lo$$
$$KEtot(t) = KErot(t) + KEtrans(t) = KEo$$

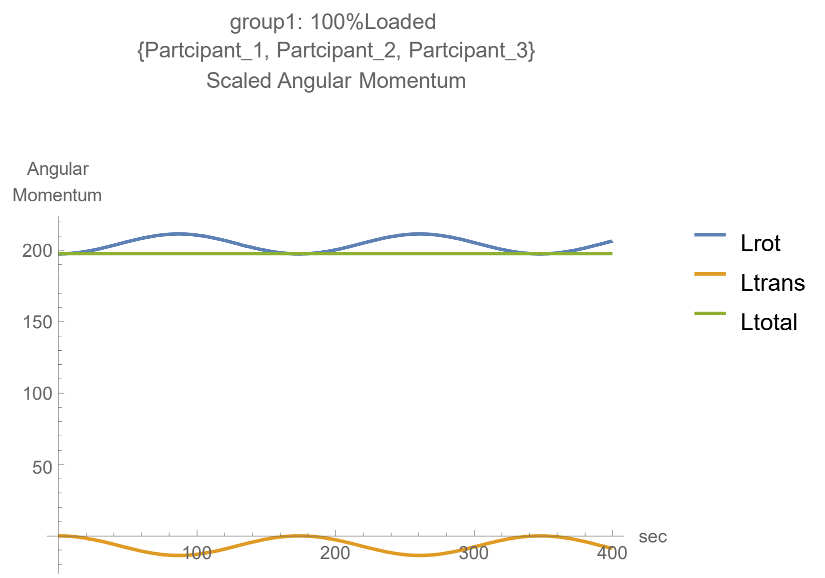
Figure 4 depicts $\{Px(t), Py(t), Ltot(t), KEtot(t)\}$ for Group 1 SpinTransit submissions, computed directly from participant-supplied tabular time histories of the motion variables. The required constancy of all four quantities is apparent, and speaks to the unequivocal compliance with Newtonian conservation laws by all members of Group 1.

Some consequences of the conservation laws may be unintuitive or paradoxical to even a trained engineer: A time-*variable* yaw rate (Fig 1b) is associated with a time-*independent* value of *Ltot*; time-*variable* {*Vx, Vy*} are associated with *constant* values of {*Px, Py*}.The paradox is resolved once it is understood there is a continual, invisible exchange of energy and momentum between vessel and fluid in this precisely choreographed Newtonian waltz. A *Py* of zero is the sum of two equal nonzero contributions (fluid and vessel), oscillating out of phase. The great Horace Lamb, not known to indulge in overstatement, quipped that these peculiar results were "very interesting" [3].

There is little to discuss regarding the non-conservation of {*Px, Py, Ltot, KEtot*} in Groups 2 and 3, shown in Figures 5 and 6; no member of either group exhibits the required constancy of these conserved quantities. All are therefore Newtonian non-compliant (NNC), presumably with meaningful implications for performance estimates past, present, and future.

Figure 4. Newtonian Compliant Momentum and Energy History: Group 1





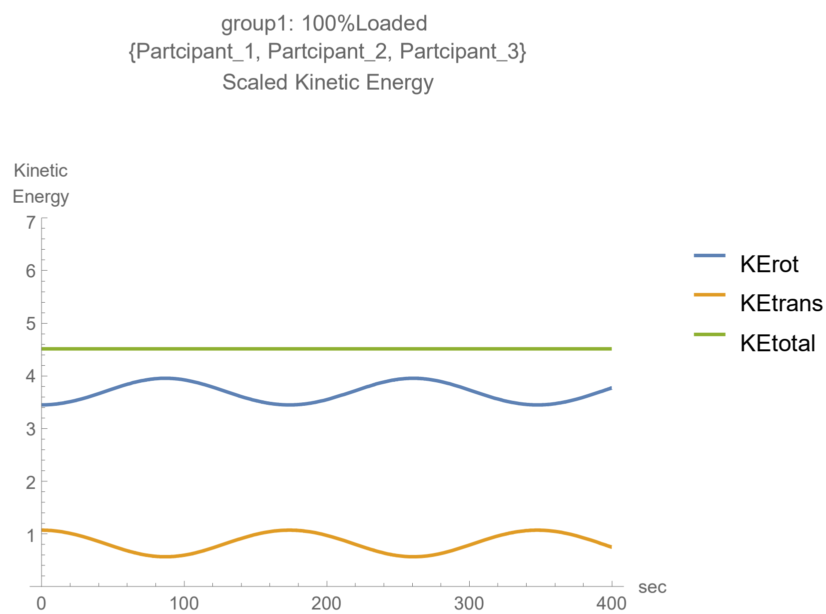
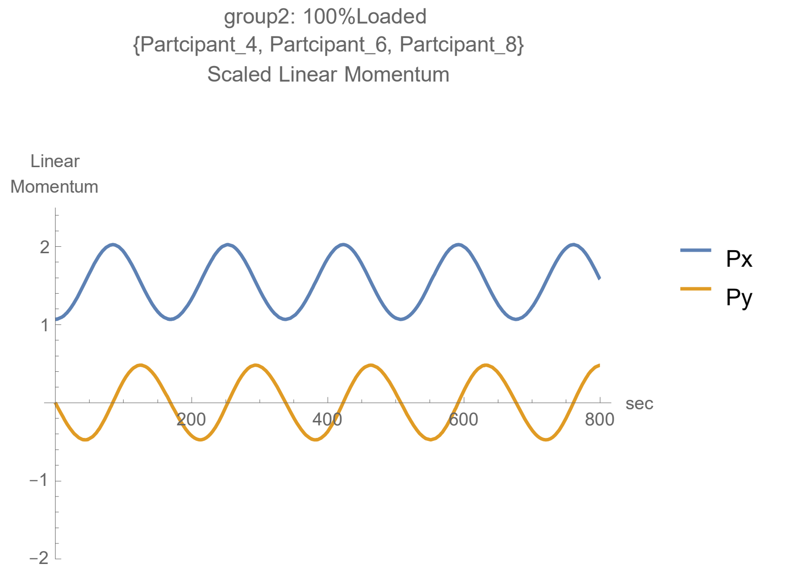
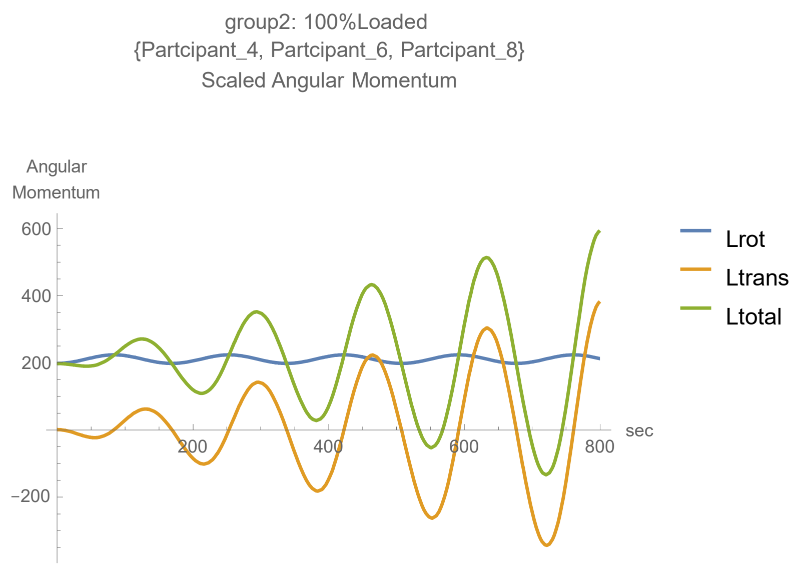


Figure 5. Newtonian Non-Compliant Momentum and Energy History: Group 2





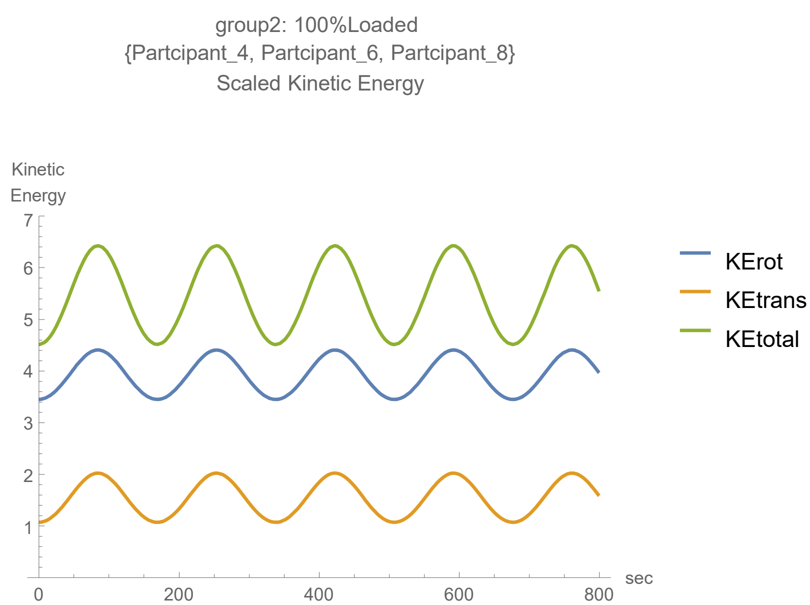
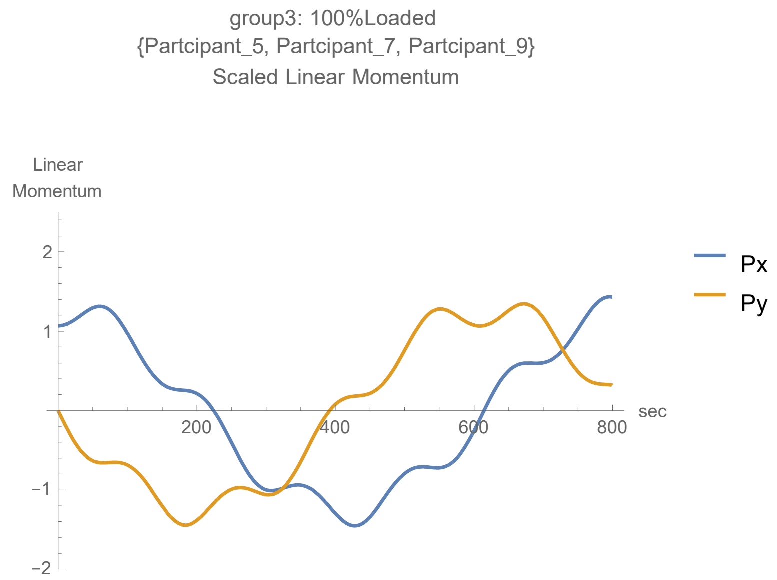
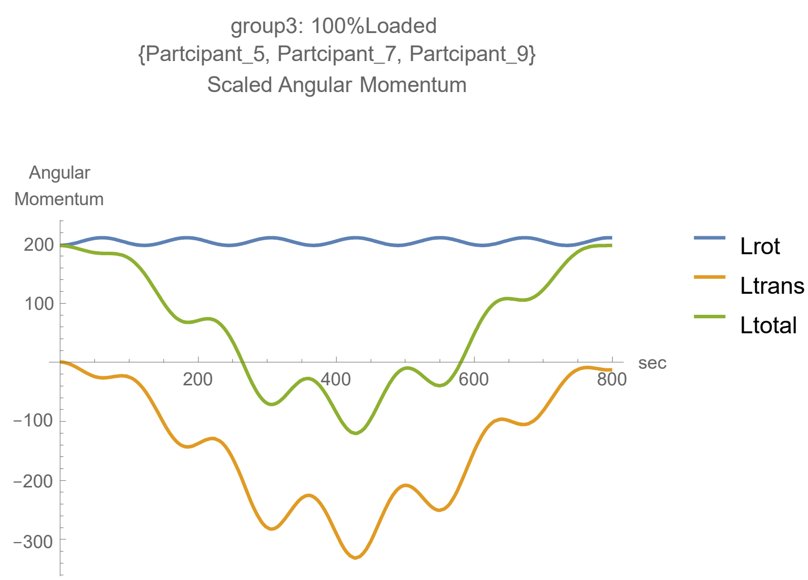
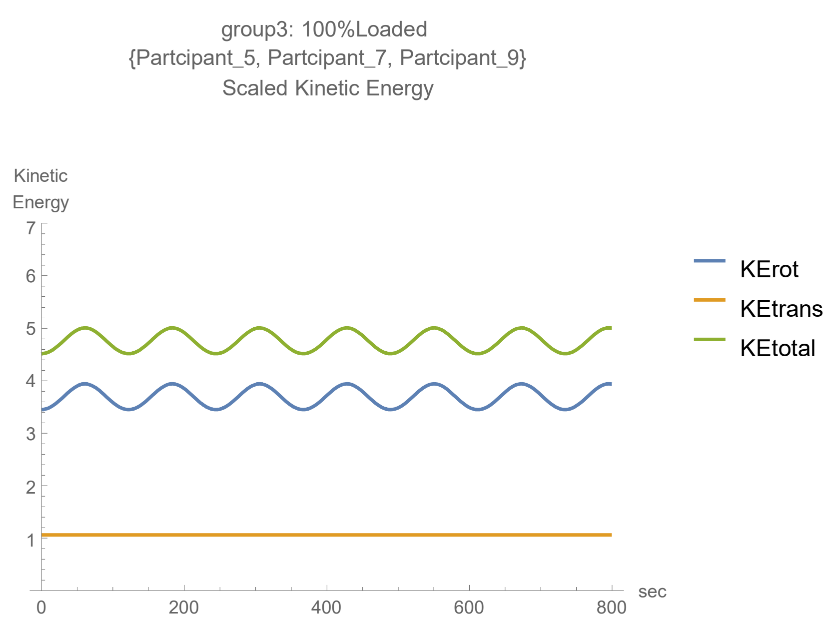


Figure 6. Newtonian Non-Compliant Momentum and Energy History: Group 3







13 Relevance to Realistic Weather-Vane Capable Floating Systems

We wish to respond briefly to a common refrain made by some software vendors and experienced offshore system analysts: that the SpinMoor and SpinTransit exercises are fundamentally irrelevant to "real systems" which sport the inevitable complications of hydrodynamic dissipation, wind, waves, and current, damping from moorings and other submerged slender members, etc., and that those "real systems" are so complex that they can only be rationally analyzed numerically by means of "tuning" simulation parameters to accommodate model test measurements of vessel response. The unspoken implication of this notion is that the Newtonian shortcomings exposed in the SpinMoor and SpinTransit studies are "noise" when compared to the complexities of the real world.

The SpinMoor model was designed to elicit a qualitatively similar response to events universally acknowledged to produce abrupt reversal of vessel orientation in weather-vane capable systems responding to transient forcing conditions building from astern (wind squall, advecting current eddy, etc.).

The specific issue of relevance of the simplified SpinMoor model was comprehensively addressed in several SpinMoor report Appendices, but those demonstrations have not, to date, generated much traction in squall analysis circles, despite considerable ongoing activity, including a multi-year squall JIP, still underway [7]. The SpinMoor Appendix VII, VIII and IX analyses, which were developed to quantify, for a production turret moored FPSO with realistic mooring and metocean environment, the consequences of "L" versus "S" simulation differences, highlighted *two* central issues related to design analyses for squall conditions:

1. The "Design Condition" for weather-vane capable systems cannot be meaningfully captured without an enormous number of unique time-domain executions (over 1 million simulation runs were used in the turret system analyses referenced in SpinMoor Appendices VII-IX).

2. System offsets and loads associated with the subset of worst-case events, obtained per the above filtering process, show approximately the same "S" versus "L" load underestimation ratios as those witnessed in the SpinMoor report; i.e., approximately a factor of two in the maximum turret load and offset for a fully loaded vessel.

14 Simulation "Validation" of NNC Simulation Models

Some analysts, informed of the NNC status of their software of choice, argue that an incorrect implementation of Newton's Laws in an offshore analysis tool is tolerable, provided Newtonian non-compliance consequences can be "corrected" by suitable ad-hoc adjustment of available parameters on the basis of model test measurements. We believe this practice, and this approach to simulation "validation", is reckless and irresponsible.

The foundation of *all* numerical simulations of floating mechanical systems is a rigorous Newtonian mathematical model of bodies operating in an ideal, inviscid fluid. Atop this idealized foundation is layered defensible accommodations for viscous effects, usually via a substantial collection of drag coefficients applied to vessel, submerged slender members and structures, etc., which coefficients are ultimately subjected to unsupervised user adjustments.

It should be self-evident that starting from a Newtonian foundation *compromised at the outset*, and then overlaying said foundation with user-adjustable forcing and/or damping mechanisms, regardless of their sophistication, will inevitably lead to compromised response estimates of unknowable quality.

15 Relevance to "Statistically Stationary" Design Environments

One ingredient common to NNC simulations in both SpinMoor and SpinTransit scenarios: unsatisfactory modeling of large yaw excursions and rates. It is reasonable to ask just how *much* yaw is necessary to elicit significant dynamical errors in NNC programs. These questions go beyond the scope of this report, but the following is worth noting:

With regard to large yaw events, the common configuration of an internal turret produces a dynamical system in which large yaw events can occur even in conventional "statistically stationary" environments. These systems have two energetically equivalent mean yaw headings in unidirectional waves, and can from time to time transition between the two mean "yaw islands of stability" with a resulting large change in mean heading adding to the already substantial RMS yawing. The DeepStar wave basin model test series of 2001-2002 [5, 6], whose vessel was the same 200 kdwt tanker used in the SpinMoor and SpinTransit studies, but with an internal turret located well aft of the bow, experienced yaw extremes in hurricane wave-only conditions in excess of ±20°, thereby experiencing ~40° net yaw events. How might simulated motion and load estimates of those conditions suffer from the Newtonian non-compliance exhibited by simulations in SpinTransit Groups 2 and 3, or SpinMoor Group "S"? At this point, we do not know. We do know, however, that the agreement between simulation and measurement in those DeepStar tests was not good [5, 6].

Acknowledgements

We wish to gratefully acknowledge the time, expertise, and ongoing support of two individuals who provided valuable input and guidance throughout the explorations leading ultimately to the SpinTransit study:

Caspar Heyl, Shell International Exploration and Production Co.
Arun Duggal, SOFEC, Inc.

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Appendices

I	SpinTransit Invitation and Protocol
II	SpinTransit FAQ
III	SpinTransit 100% Load Case Results
IV	SpinTransit 40% Load Case Results

References & Links

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Appendix I

SpinTransit Invitation and Protocol

Study Invitation:

To all SpinMoor participants:

The SpinMoor study and its surprising findings have generated considerable interest amongst mooring specialists worldwide. I have appended a summary of exchanges that took place recently on a rather large ISO mooring mailing list that you may find interesting.

One take-away from this exchange of comments is that a second comparative study, similar in many respects to the SpinMoor (we are calling it the "SpinTransit" study) will be of value in better understanding the bifurcated nature of the SpinMoor results. This follow-on study is specifically intended to help evaluate the relevance of the so-called "maneuvering equations" or "maneuvering forces" to the SpinMoor study.

I hope you will be willing and able to participate in this project.

There is no mooring system involved in the SpinTransit, and the vessel is the same 200 kdwt tanker used for the SpinMoor study, so setup and execution should be extremely straightforward.

I have appended the SpinTransit protocol document for your consideration. Please contact me directly if you have any questions, comments, or reservations about participating. Note that the SpinTransit study will not be limited to SpinMoor participants, but will be open to participation by any interested simulation vendor.

Please let me know if you can participate and if so, an approximate time frame for the preparation of your contribution.

As in the SpinMoor study, results will be anonymized; we will further anonymize results by re-assigning participant numbers; for example, SpinMoor Participant 1 and SpinTransit Participant 1 will not be the same.

Best Regards and many thanks for your participation in the SpinMoor project.

Richard Hartman
SeaSoft Systems

SpinTransit Protocol: Rev. 5

Protocol Change List:

Rev. 3: First distribution of protocol
Rev. 4: Add equation/assignment numbers; correct typo in Munk moment sign in eq. 4
Rev. 5: Typos

The SpinTransit protocol is for most purposes simply the SpinMoor™ protocol without moorings. To quote from the SpinMoor Report, Appendix III [1]:

"The SpinTransit protocol, as the name implies, calls for the analysis of an unmoored vessel, simultaneously spinning and translating in a perfect fluid, with no dissipative mechanisms whatever (i.e., OCIMF surge and sway coefficients {Cx, Cy} are both identically zero). In the SpinTransit scenario, however, the (non-dissipative) Munk moment is included via a suitably crafted OCIMF-style yaw coefficient {Cz}. Like the SpinMoor, this is a condition of little, if any, direct relevance to real-life problems in the offshore industry, but whose simple dynamics offers a thicket of numerical and methodological cracks and crevices to trip simulation software."

I. Vessel:

The SpinTransit vessel is the same stock Marin 200 dwt tanker used for the SpinMoor study. The mass properties, as in the SpinMoor protocol, are specified in Johann Wichers' Ph.D. thesis; these numerical particulars and others can be found in the accompanying Excel spreadsheet.

II. Scenario:

The vessel floats in an ideal fluid; all motions are considered "quasi-static"; wave-frequency fluid responses are assumed negligible. This is a 3-DOF problem that should nonetheless present no difficulties to users of 6-DOF simulation tools. For users whose simulations can produce either 3- or 6- DOF output, you are free to submit both if you wish, particularly if you find significant differences between the two.

II. Dynamical environment:

According to D'Alembert any floating or submerged body, regardless of shape, once set in motion in a perfect fluid and released, feels no net lateral force, and experiences no dissipation of energy arising from its subsequent motion relative to the fluid, which motion will therefore be perpetual. However, in this circumstance a moment, the so-called Munk moment, acts on the body; this moment likewise produces no dissipation. Its magnitude depends only upon the relative motion of the CG through the fluid. See further discussion below.

This moment is responsible for the instability of vessel motions parallel to their centerline, which moment causes a drifting vessel to tend towards an abeam-drift configuration; that is, head-on flow is an unstable condition; beam-on flow is a stable condition.

We wish to repeat, for emphasis, that for time $T > 0$ the only forces permitted to act on the vessel in SpinTransit are the reactions associated with potential flow about the tanker arising from its motions.

Specifically, this means no externally applied forces or moments (except, possibly, those required to set up the initial condition at times $T < 0$), and no user-specified interventions such as adjustable surge, sway, yaw, or sway-yaw coupled damping. Since the net potential force acting on the vessel vanishes (D'Alembert), the only dynamic input permitted for $T > 0$ is the non-dissipative Munk moment; the resulting motion will be perpetual.

III. Munk moment modeled with OCIMF square-law moments:

For our highly symmetric simplified vessel, the Munk moment can be written:

1. Munk moment = -0.5*Mdisp*(vmc22-vmc11)*V^2*Sin[2*theta]

Here, Mdisp is the vessel displacement mass (drydock mass), {vmc11,vmc22} are the vessel virtual mass coefficients in surge and sway. V is the vessel's velocity at its center of gravity (cg velocity). Theta is the instantaneous angle between the vessel centerline and the relative flow velocity vector.

To emphasize: theta is *not* the vessel yaw angle but is the relative-to-bow current angle in the vessel-fixed system (so 0 degrees represents flow from stern-to-bow). Thus, for example, with vessel pointed North (yaw = 0) and with CG progressing NorthEast bound (315 degrees in a right-hand global system), the relative-flow theta will be 135 degrees, producing a positive Munk moment in the right-handed coordinate system.

With respect to the above examples, if your simulation base coordinate systems are left-handed, the comments will need to be appropriately adjusted for your system.

From the accompanying spreadsheet, the SpinTransit vessel mass quantities in {loaded, ballasted} conditions are:

2. Loaded: {vmc11, vmc22} ~ {1.065, 2.022}; Mdisp ~ 2.409 E8 kg
3. Ballasted: {vmc11, vmc22} ~ {1.027, 1.578}; Mdisp ~ 9.118 E7 kg

Note 1: Some simulations automatically include the Munk moment using either internally computed or user-specified added mass values. For simulations that do not compute this moment automatically, it can be included without compromise via a properly crafted OCIMF moment coefficient which produces the Munk moment specified above. Using the conventional definition for OCIMF yaw moment associated with a coefficient CzMunk[theta], we need:

4. 0.5*rho*V^2*LWL^2*D*CzMunk[theta] = -0.5*Mdisp*(vmc22-vmc11)*V^2*Sin[2*theta]

so that

5. CzMunk[theta] = -(vmc22-vmc11)*Sin[2*theta]*[Mdisp/(rho*LWL^2*D)]

Here, LWL = vessel waterline length, D = draft and rho = water mass density.

So, if your simulation includes the Munk moment by default, you must use null OCIMF drag coefficients or you will double-count the Munk moment; that is, you need:

6. {Cx, Cy, Cz} = {0, 0, 0}.

If your simulation does NOT compute the Munk moment internally, you can use the following OCIMF-style square-law coefficients to produce it:

7. {Cx, Cy, Cz} = {0, 0, CzMunk[theta]), with CzMunk[theta] computed per the above.

Here, the three coordinates refer to surge [x], sway [y] and yaw [z].

Note 2: Simulations based on the so-called "maneuvering equations" most likely include the Munk moment automatically. Please consult your simulation's documentation.

Note 3: The accompanying protocol spreadsheet provides tables of CzMunk[theta] for the three 200 dwt draft cases in Wichers' thesis; these tables can be used to check magnitudes, signs, etc., in your own CzMunk implementation, or can be used directly via interpolation.

IV. Initial condition:

At T = 0, the vessel centerline is aligned North-South, and the vessel moves forward (Northward) with a velocity of 1 meter/second. It simultaneously rotates with an angular (yaw) rate of one degree/second counterclockwise.

How this initial condition is established is irrelevant; if initial conditions are not accommodated by your simulation, you can achieve them by supplying an appropriate linear and angular impulse or force/moment history (e.g., a short linear + angular acceleration burst ending at the instant T = 0). The impulsive force and moment required to achieve the initial condition are readily computed from the vessel mass and added mass properties and the specified rates, which rates should be met within 2%:

8. $0.98 <$ speed or yaw rate < 1.02

The vessel motion continues to evolve with time, spinning and translating indefinitely.

IV. Output stream Protocol:

The SpinTransit output stream comprises the vessel CG location {Xcg, Ycg}in meters, orientation (yaw angle in degrees) and both their first and second order time derivatives (linear and angular velocities and accelerations) in a right-handed coordinate system with zero towards the North.

Please provide tab-delimited numerical tables as a function of time:

{T, Xcg, Ycg, Z(Yaw), Vxcg, Vycg, dZ/dt}

in a single table with each row containing a single time step; see the initial condition time step row below for guidance.

T(sec)	X	Y	Yaw	Vx	Vy	dZ/dt	Ax	Ay	d^2Z/dt^2
0	0	0	0	1	0	1	0	0	0

Here Vx (m/sec), Ax (m/sec^2), etc. are {x,y} velocity and acceleration values; dZ/dt (deg/sec) and d^2Z/dt^2 (deg/sec^2) are the first and second time derivatives of the yaw angle.

Note: The derivatives are of value to monitor numerical jitter or instability in the time-step solvers used; these derivatives should be readily available as they are the fundamental components of the governing second order dynamical equations. If acceleration reports cannot be conveniently obtained, please advise and provide position and rate data, which we can differentiate numerically if necessary to obtain second derivatives.

Time interval between data points: please provide something between 1/2 and 1 seconds; they do not need to be precise integers or fractions.

Please report all quantities to 8 or more significant digits, at each time step between T = 0 to T = 7200 prototype seconds (~ 20 rotations of the vessel and ~ 7.2 cumulative kilometers of cg motion) so we can evaluate the long-term stability of the numerical solver algorithms.

Please refer any questions to:

Richard Hartman
SeaSoft Systems
seasoft@west.net

Data copied from Wichers' Thesis pp 38			Loaded	Mid	Ballast
Loading condition		%	100.00	60.00	25.00
Draft in per cent ofloaded draft		%	100.00	70.00	40.00
Length between perpendiculars L	L	m	310.00	310.00	310.00
Breadth B	B	m	47.17	47.17	47.17
Depth H	H	m	29.70	29.70	29.70
Draft T	T	m	18.90	13.23	7.56
Wetted area S	S	m^2	22804.00	18670.00	13902.00
Displacement volume V	V	m^3	234994.00	159698.00	88956.00
Mass M	M	tf*s^2/m	24553.00	16686.00	9295.00
Centre of buoyancy forward FB of sectior	FB	m	6.60	9.04	10.46
Centre of gravity above keel KG	KG	m	13.32	11.55	13.32
Metacentric height transverse GMt	GMt	m	5.78	8.66	13.94
Metacentric height longitudinal GMl	GMl	m	403.83	403.83	403.83
Transverse radius of gyration in air kll	k11	m	14.77	15.02	15.30
Longitudinal radius of gyration in air k22	k22	m	77.47	77.52	82.15
Yaw radius of gyration in air k66	k66	m	79.30	83.81	83.90
Lateral wind area of superstructure (aft)	Ax	m^2	922.00	922.00	922.00
Transverse area of superstructure (aft)	Ay	m^2	853.00	853.00	853.00

Zero frequency added mass matrix (water depth 82.5 m)

			Loaded	Mid	Ballast
Thesis values					
	a11	tf*s^2/m	1594.0	755.0	250.0
	a22	tf*s^2/m	25092.0	10940.0	5375.0
Fore-aft symmetric vessel	a26	tf*s^2	0.0	0.0	0.0
Fore-aft symmetric vessel	a62	tf*s^2	0.0	0.0	0.0
	a66	tf*s^2*m	123510000.0	59607700.0	23200000.0
Added Masses in Kilograms					
	a11	kg	1.56371E+07	7.40655E+06	2.45250E+06
	a22	kg	2.46153E+08	1.07321E+08	5.27288E+07
Fore-aft symmetric vessel	a26	kg*m	0.00000E+00	0.00000E+00	0.00000E+00
Fore-aft symmetric vessel	a62	kg*m	0.00000E+00	0.00000E+00	0.00000E+00
	a66	kg*m^2	1.21163E+12	5.84752E+11	2.27592E+11
Displaced Mass	Mdisp	kg	2.40865E+08	1.63690E+08	9.11840E+07
Virtual Mass Coefficients	vmc11	dimensionless	1.06492	1.04525	1.02690
	vmc22	dimensionless	2.02195	1.65564	1.57827
	vmc22-vmc11	dimensionless	0.95703	0.61039	0.55137

OCIMF Current Areas

Head-on (Transverse)	Axc	m^2	891.51	624.06	356.61
Beam-on (Lateral)	Ayc	m^2	5859.00	4101.30	2343.60

OCIMF Wind Areas

Head-on (Transverse)	Axw	m^2	1362.44	1629.89	1897.34
Beam-on (Lateral)	Ayw	m^2	4201.00	5958.70	7716.40

Cz = -(vmc22-vmc11)*Sin[2*theta]*[Mdisp/(rho*LWL^2*D)]

OCIMF-style Munk Moment Coefficient

Theta (deg)	Cx	Cy	Loaded Cz	Mid Cz	Ballast Cz
0.00	0.00	0.00	0.0000000	0.0000000	0.0000000
5.00	0.00	0.00	-0.0215011	-0.0133135	-0.0117237
10.00	0.00	0.00	-0.0423489	-0.0262225	-0.0230911
15.00	0.00	0.00	-0.0619100	-0.0383348	-0.0337570
20.00	0.00	0.00	-0.0795900	-0.0492822	-0.0433972
25.00	0.00	0.00	-0.0948516	-0.0587323	-0.0517187
30.00	0.00	0.00	-0.1072313	-0.0663978	-0.0584688
35.00	0.00	0.00	-0.1163528	-0.0720458	-0.0634424
40.00	0.00	0.00	-0.1219389	-0.0755048	-0.0664883
45.00	0.00	0.00	-0.1238200	-0.0766696	-0.0675140
50.00	0.00	0.00	-0.1219389	-0.0755048	-0.0664883
55.00	0.00	0.00	-0.1163528	-0.0720458	-0.0634424
60.00	0.00	0.00	-0.1072313	-0.0663978	-0.0584688
65.00	0.00	0.00	-0.0948516	-0.0587323	-0.0517187
70.00	0.00	0.00	-0.0795900	-0.0492822	-0.0433972
75.00	0.00	0.00	-0.0619100	-0.0383348	-0.0337570
80.00	0.00	0.00	-0.0423489	-0.0262225	-0.0230911
85.00	0.00	0.00	-0.0215011	-0.0133135	-0.0117237
90.00	0.00	0.00	0.0000000	0.0000000	0.0000000
95.00	0.00	0.00	0.0215011	0.0133135	0.0117237
100.00	0.00	0.00	0.0423489	0.0262225	0.0230911
105.00	0.00	0.00	0.0619100	0.0383348	0.0337570
110.00	0.00	0.00	0.0795900	0.0492822	0.0433972
115.00	0.00	0.00	0.0948516	0.0587323	0.0517187
120.00	0.00	0.00	0.1072313	0.0663978	0.0584688
125.00	0.00	0.00	0.1163528	0.0720458	0.0634424
130.00	0.00	0.00	0.1219389	0.0755048	0.0664883
135.00	0.00	0.00	0.1238200	0.0766696	0.0675140
140.00	0.00	0.00	0.1219389	0.0755048	0.0664883
145.00	0.00	0.00	0.1163528	0.0720458	0.0634424
150.00	0.00	0.00	0.1072313	0.0663978	0.0584688
155.00	0.00	0.00	0.0948516	0.0587323	0.0517187
160.00	0.00	0.00	0.0795900	0.0492822	0.0433972
165.00	0.00	0.00	0.0619100	0.0383348	0.0337570
170.00	0.00	0.00	0.0423489	0.0262225	0.0230911
175.00	0.00	0.00	0.0215011	0.0133135	0.0117237
180.00	0.00	0.00	0.0000000	0.0000000	0.0000000
185.00	0.00	0.00	-0.0215011	-0.0133135	-0.0117237
190.00	0.00	0.00	-0.0423489	-0.0262225	-0.0230911
195.00	0.00	0.00	-0.0619100	-0.0383348	-0.0337570
200.00	0.00	0.00	-0.0795900	-0.0492822	-0.0433972
205.00	0.00	0.00	-0.0948516	-0.0587323	-0.0517187
210.00	0.00	0.00	-0.1072313	-0.0663978	-0.0584688
215.00	0.00	0.00	-0.1163528	-0.0720458	-0.0634424
220.00	0.00	0.00	-0.1219389	-0.0755048	-0.0664883
225.00	0.00	0.00	-0.1238200	-0.0766696	-0.0675140
230.00	0.00	0.00	-0.1219389	-0.0755048	-0.0664883
235.00	0.00	0.00	-0.1163528	-0.0720458	-0.0634424
240.00	0.00	0.00	-0.1072313	-0.0663978	-0.0584688
245.00	0.00	0.00	-0.0948516	-0.0587323	-0.0517187
250.00	0.00	0.00	-0.0795900	-0.0492822	-0.0433972
255.00	0.00	0.00	-0.0619100	-0.0383348	-0.0337570
260.00	0.00	0.00	-0.0423489	-0.0262225	-0.0230911
265.00	0.00	0.00	-0.0215011	-0.0133135	-0.0117237
270.00	0.00	0.00	0.0000000	0.0000000	0.0000000
275.00	0.00	0.00	0.0215011	0.0133135	0.0117237
280.00	0.00	0.00	0.0423489	0.0262225	0.0230911
285.00	0.00	0.00	0.0619100	0.0383348	0.0337570
290.00	0.00	0.00	0.0795900	0.0492822	0.0433972
295.00	0.00	0.00	0.0948516	0.0587323	0.0517187
300.00	0.00	0.00	0.1072313	0.0663978	0.0584688
305.00	0.00	0.00	0.1163528	0.0720458	0.0634424
310.00	0.00	0.00	0.1219389	0.0755048	0.0664883
315.00	0.00	0.00	0.1238200	0.0766696	0.0675140
320.00	0.00	0.00	0.1219389	0.0755048	0.0664883
325.00	0.00	0.00	0.1163528	0.0720458	0.0634424
330.00	0.00	0.00	0.1072313	0.0663978	0.0584688
335.00	0.00	0.00	0.0948516	0.0587323	0.0517187
340.00	0.00	0.00	0.0795900	0.0492822	0.0433972
345.00	0.00	0.00	0.0619100	0.0383348	0.0337570
350.00	0.00	0.00	0.0423489	0.0262225	0.0230911
355.00	0.00	0.00	0.0215011	0.0133135	0.0117237
360.00	0.00	0.00	0.0000000	0.0000000	0.0000000

Appendix II

SpinTransit FAQ; Rev 2

Q1: Is the formula for the Munk moment given in the rev 1 protocol missing a minus sign? For a theta of 135 degrees as used in your example, the formula produces a negative moment where I would expect a positive one.

A. Yes, you are correct about the typo in the formula. This error was corrected, and the Munk moment protocol description improved, in revision 4 (and subsequent revisions) of the protocol.

Q2: Input stream: What variables are you looking for from the input stream?

A: It would be helpful to have a summary of the input data used in the simulations in case we find anomalies and need to try and track down possible typos or input errors. Screen shots would be fine if text files are not available. For participants using commercially-available software, please include a zipfile of all the data required for a 3rd party to reproduce your results using that software, and please be sure that your simulation software version is recorded somewhere in the input stream.

Q3: Output stream: Do you want movies of the vessel motion, similar to the SpinMoor.mov you supplied with the information packet?

A. No movies, please; the size becomes a problem for email attachments.

Q4: fore-aft symmetry & waterplane areas: My program requires some values that do not appear in the Marin_200kdwt.xls excel spreadsheet. What should I use for:
1. Longitudinal flotation center, longitudinal center of buoyancy (LCB)
2. Waterplane areas

A:
1. To ensure the fore-aft symmetry we are seeking, all "longitudinal" quantities (LCG, LCB, etc.) should be placed at midships in all cases.
2. The waterplane areas of the Marin 200 kdwt tanker are:
{Loaded, Ballasted} = {13,400, 12,310} m^2

Q5: GML (and, KML) value confusion: The spreadsheet Marin_200kdwt.xls shows GML the same for both loaded and ballasted. That seems unreasonable. Comments?

A: We are using all the same vessel properties that were used in the sister "SpinMoor" analysis study for convenience and everyone's sanity.

Further Background: The GML specs given in Johann Wichers' thesis were missing for the Intermediate and Ballasted cases; we therefore used the loaded value for all. Despite this being incorrect, please use the quoted value (403.83 m) for both cases so everyone will use the same numbers. The natural period of pitch will only affect those running 6 DOF codes, and there should be virtually no pitch in our waveless environment.

For 6 DOF codes with numerical stability or runaway problems in heave, roll and/or pitch, it might be useful to use a small linear damping to suppress numerical "noise" in those degrees of freedom; that should have no discernable impact on the SpinTransit output stream.

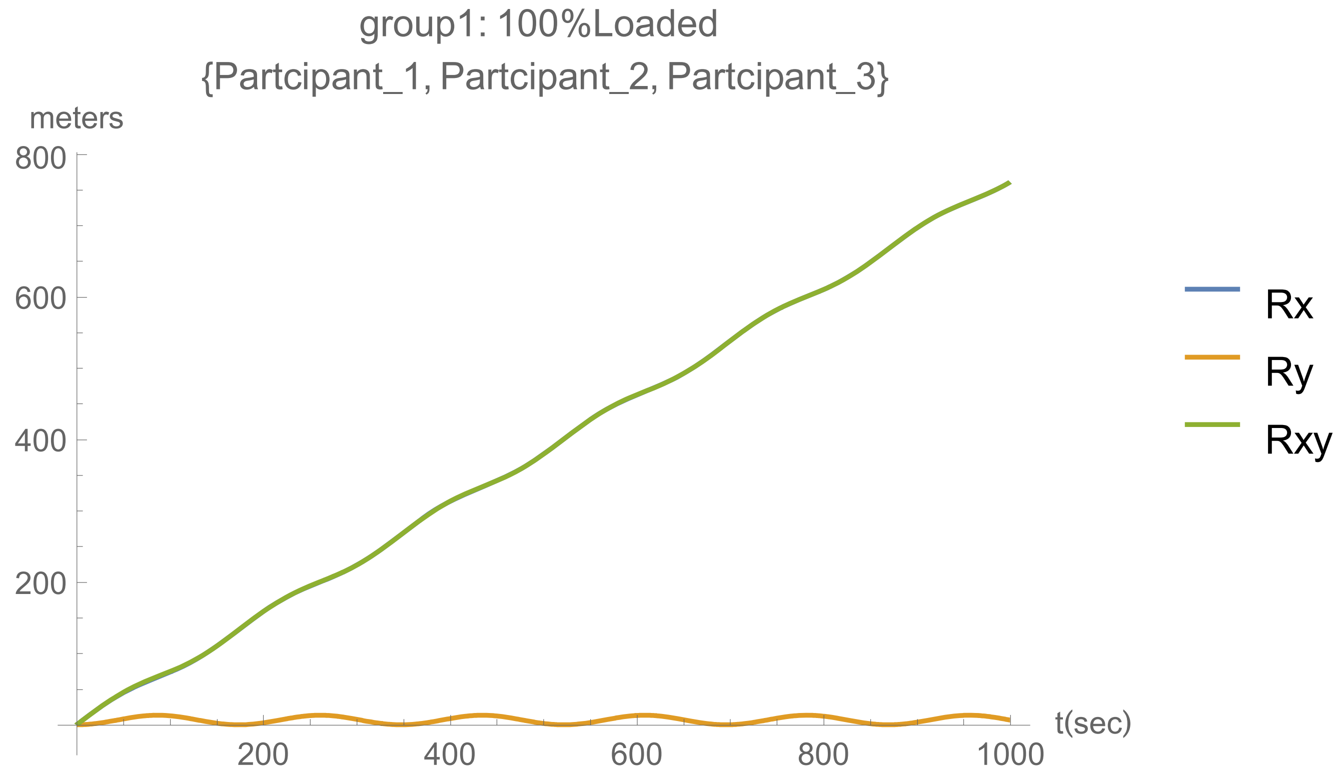
Q6: Your vessel particulars Excel spreadsheet shows three load conditions: Full, Mid and Ballast. Should we simulate all three cases?

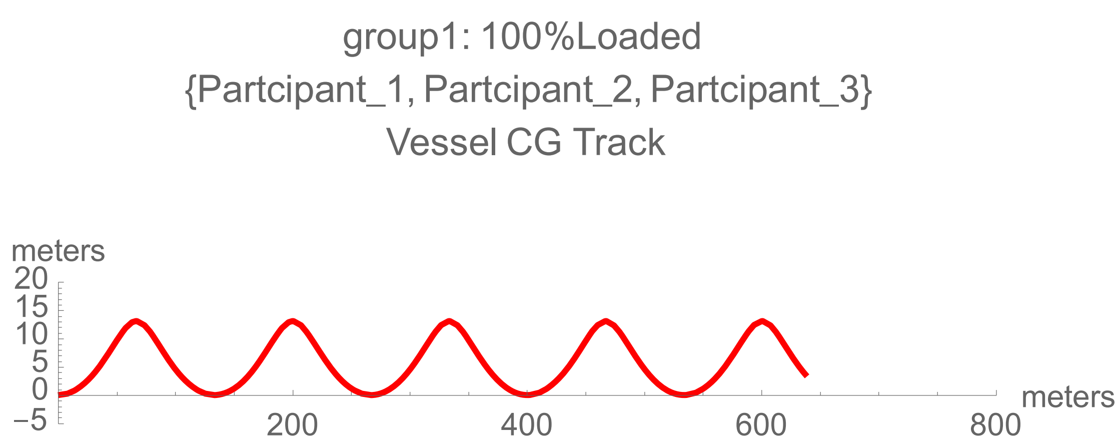
A: We only plan on using the 100% loaded and 40% ballasted cases for the comparisons, exactly as in the SpinMoor study.

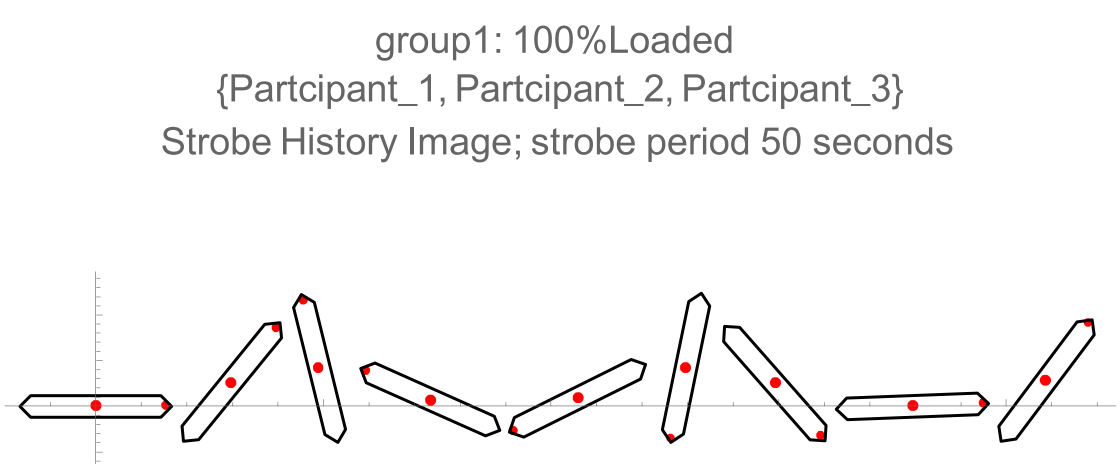
Appendix III

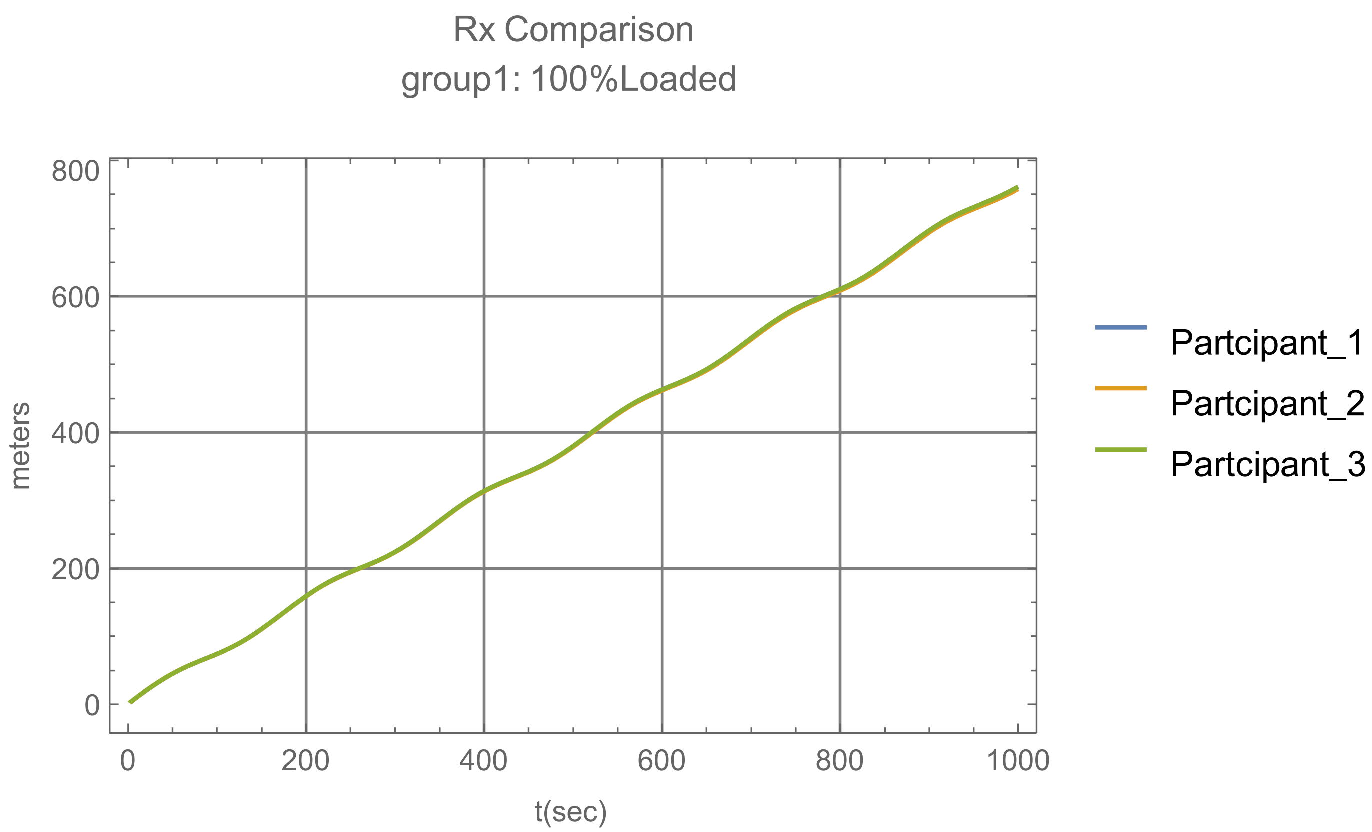
Per-Participant Graphical Summaries: 100% Load Case

Visualizations of the vessel motions for each of the nine Participants are provided on the following pages. Fundamentally identical sets of data are combined, when possible.

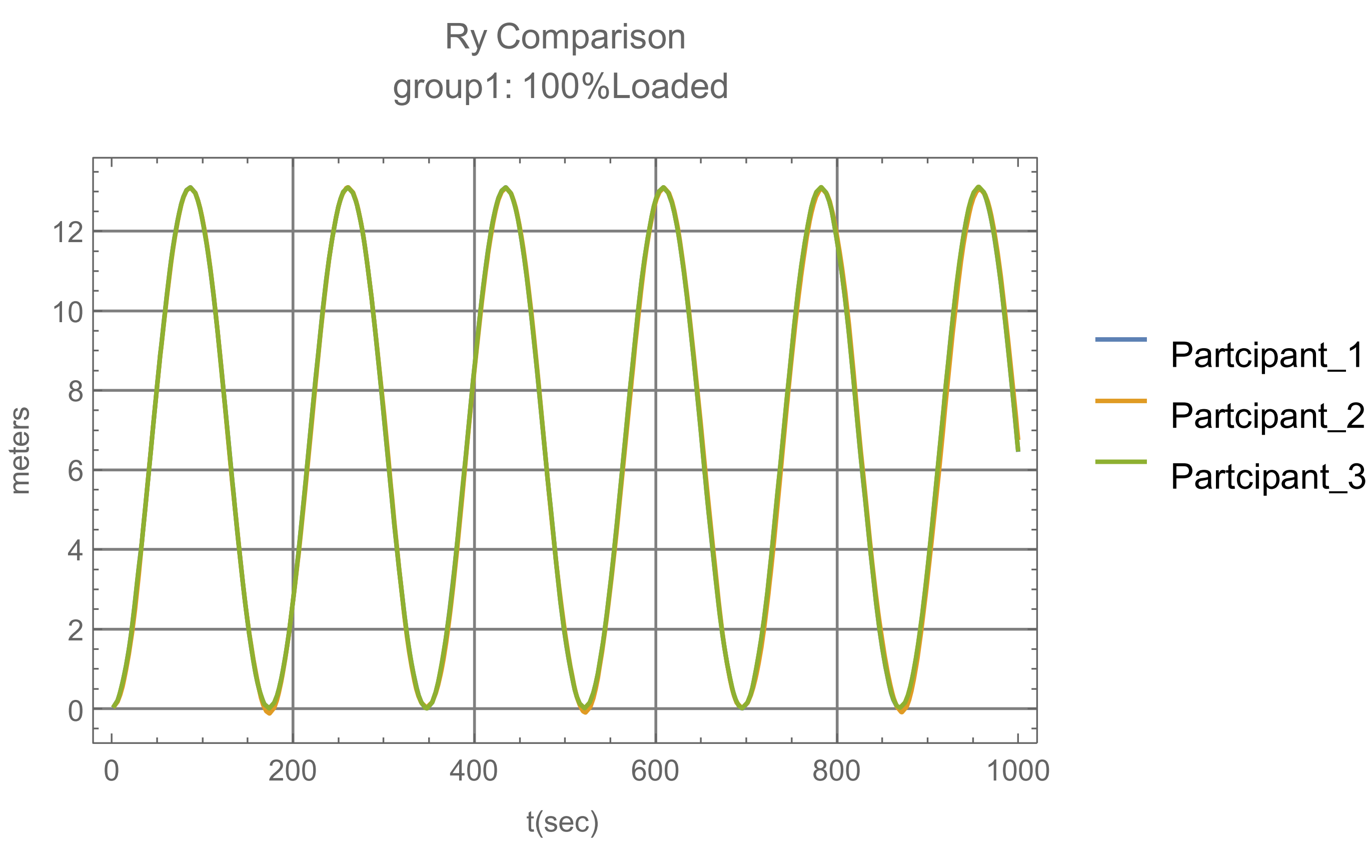

group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
meters
800
600
400
200
200
400
600
800
1000
t(sec)
Rx
Ry
Rxy


group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Vessel CG Track
meters
20
15
10
5
0
−5
200
400
600
800
meters

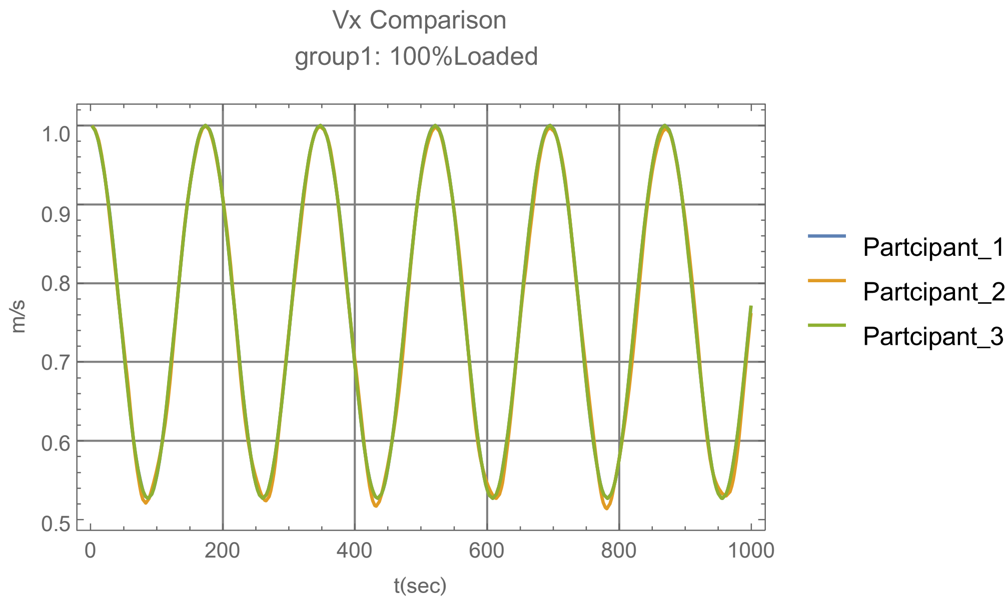

group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Strobe History Image; strobe period 50 seconds

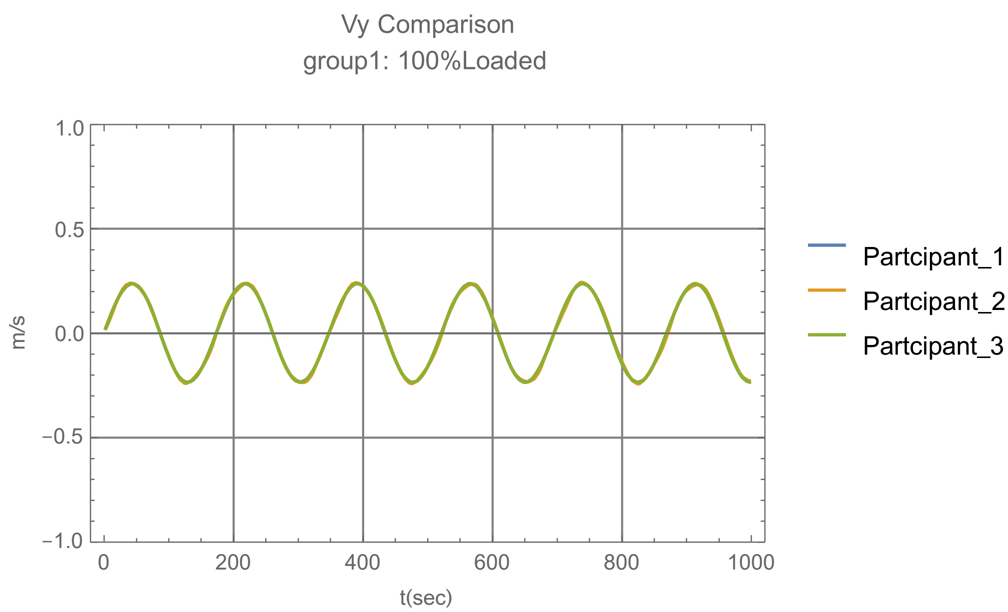


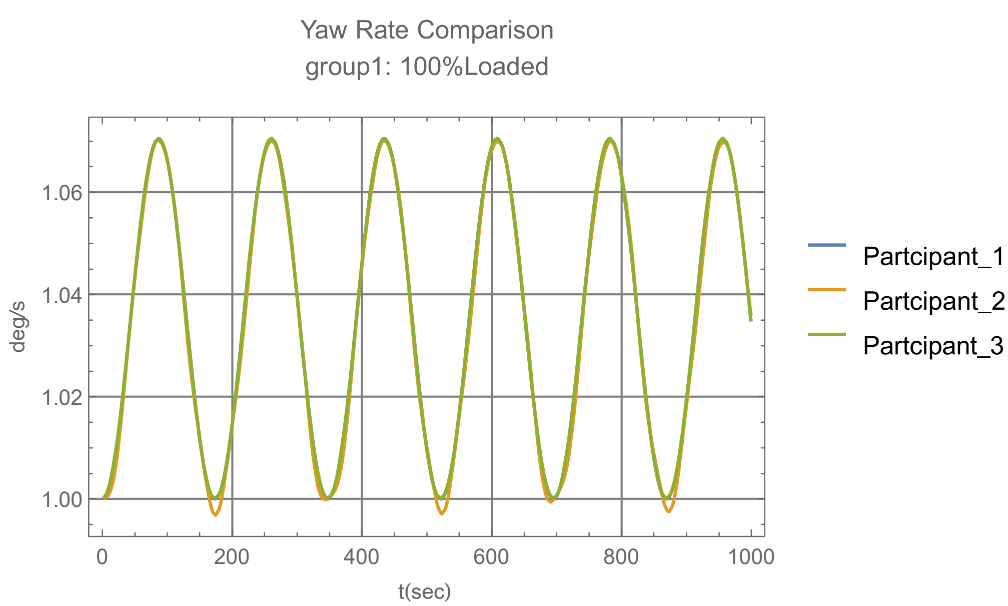
Rx Comparison
group1: 100%Loaded
meters
800
600
400
200
0
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3



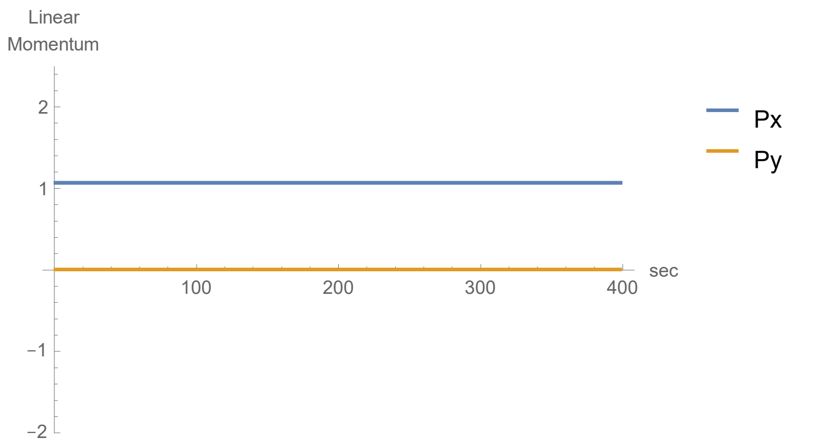
Ry Comparison
group1: 100%Loaded
meters
12
10
8
6
4
2
0
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3


Vx Comparison
group1: 100%Loaded
1.0
0.9
0.8
0.7
0.6
0.5
m/s
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3

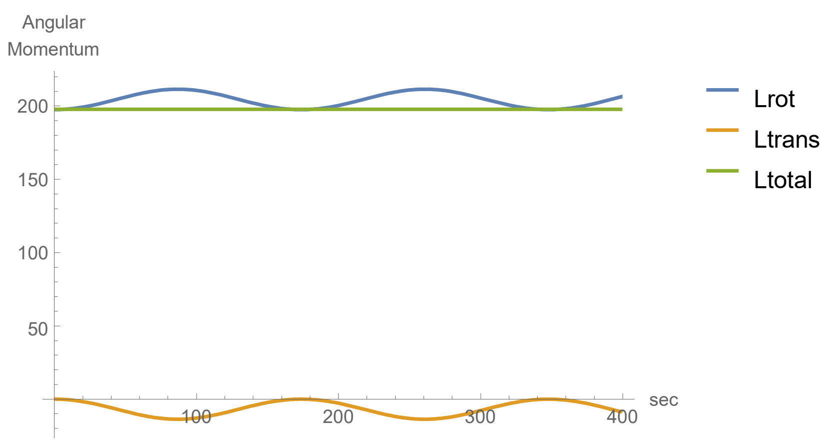

Vy Comparison
group1: 100%Loaded
1.0
0.5
0.0
−0.5
−1.0
m/s
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3


Yaw Rate Comparison
group1: 100%Loaded
1.06
1.04
1.02
1.00
deg/s
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3

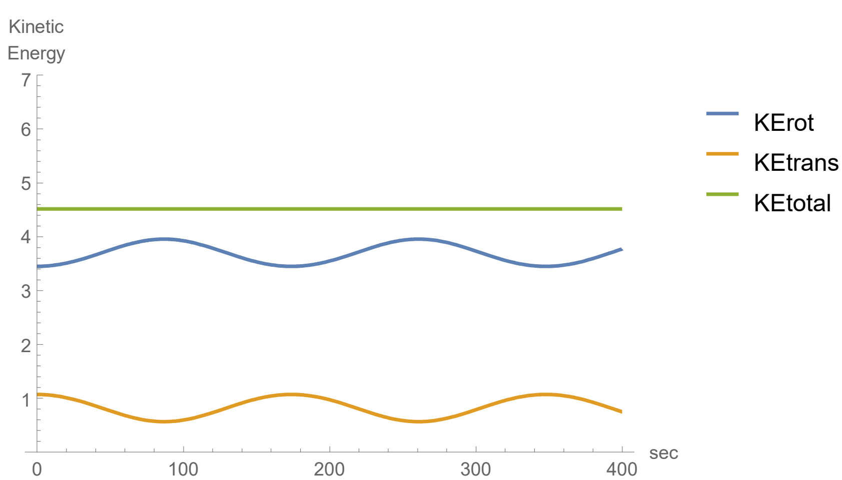
group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Linear Momentum



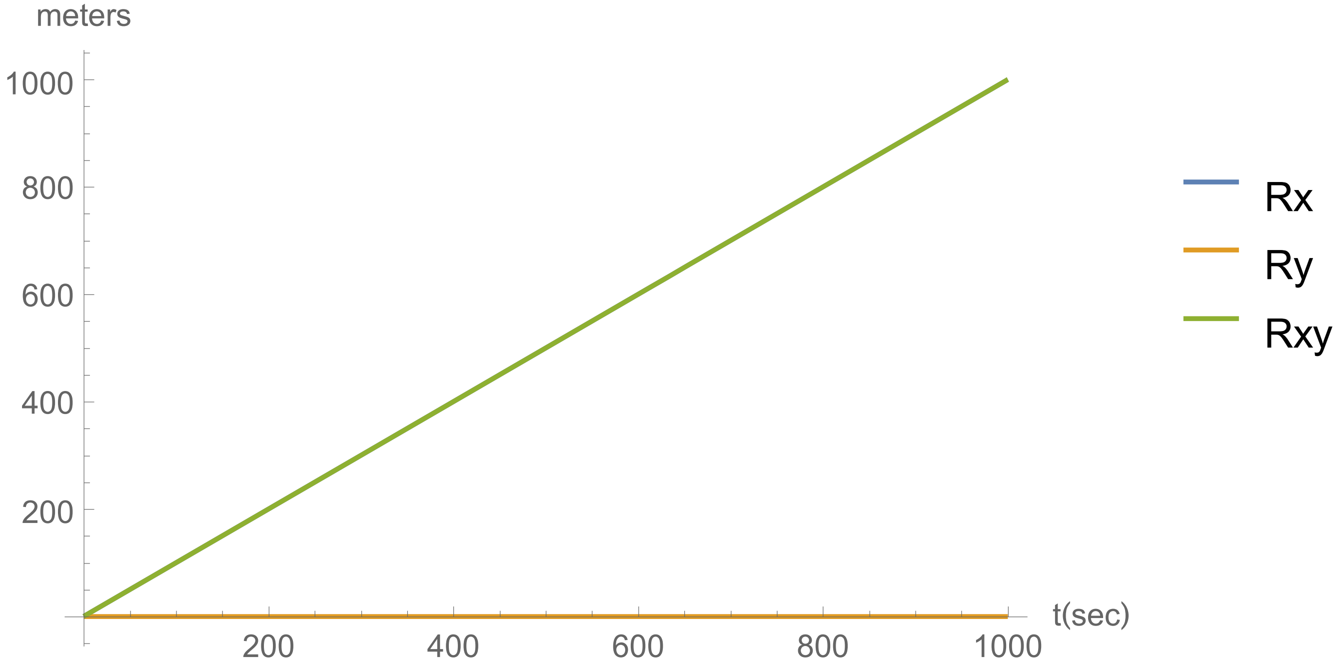
group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Angular Momentum



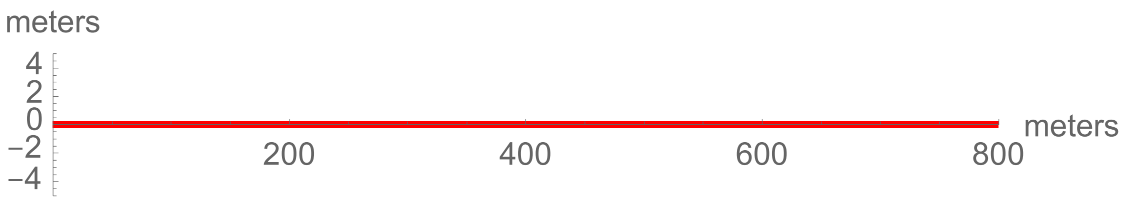
group1: 100%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Kinetic Energy



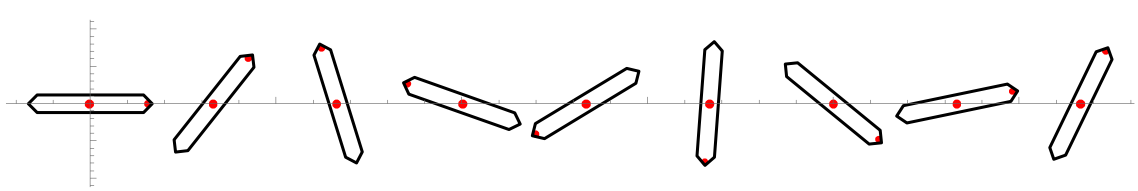
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}

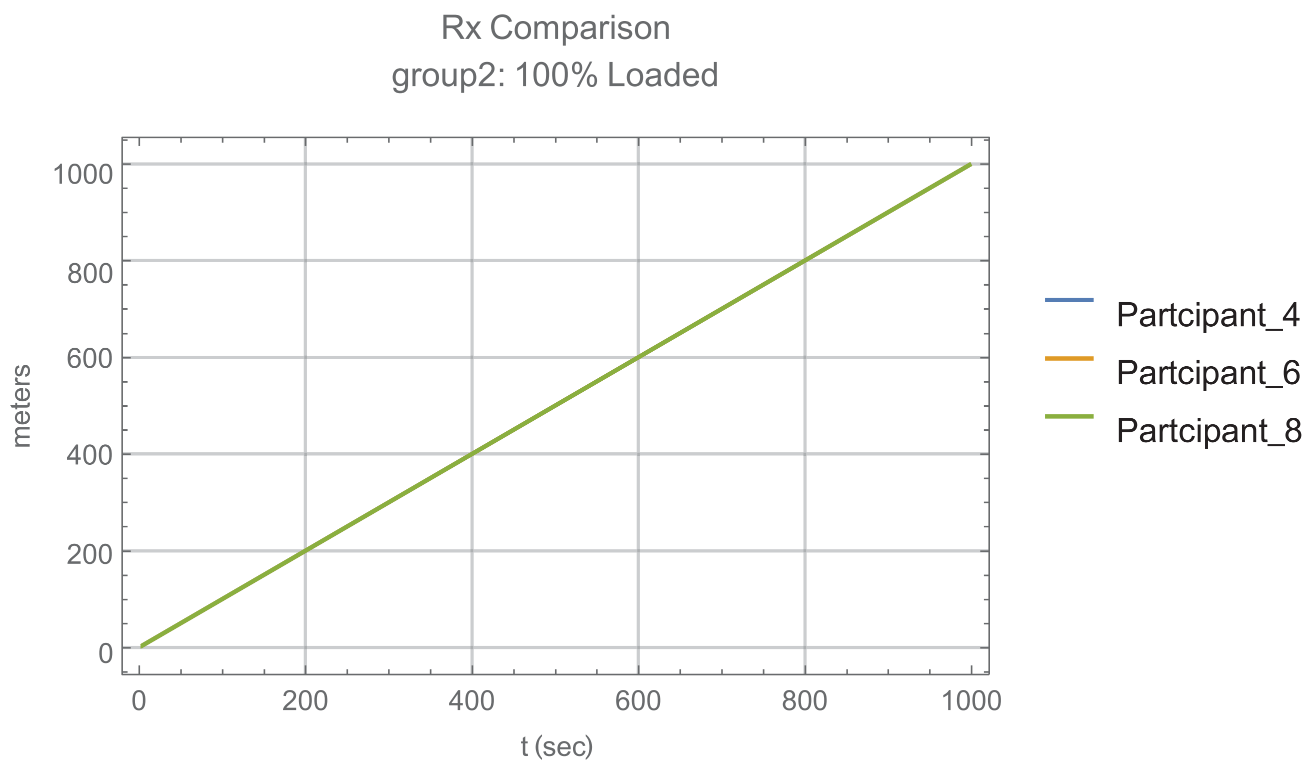


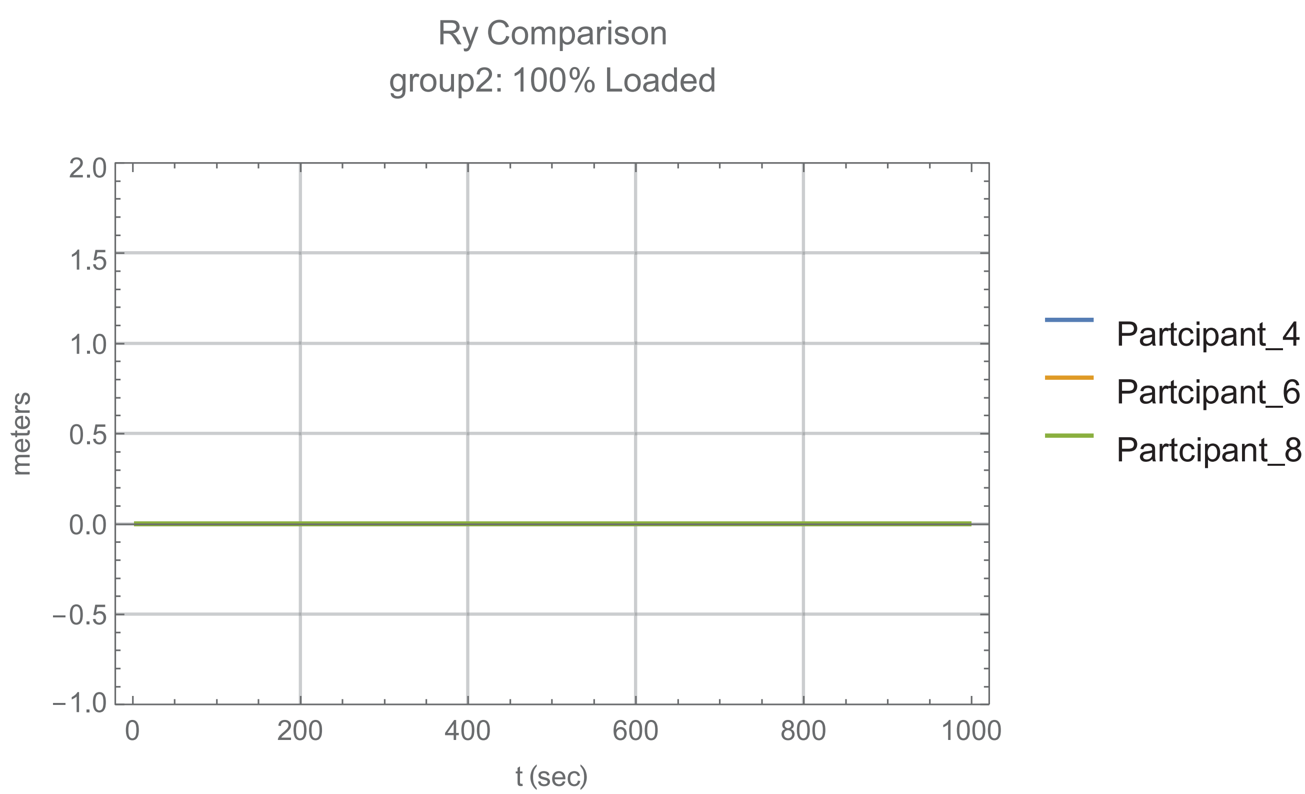
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Vessel CG Track

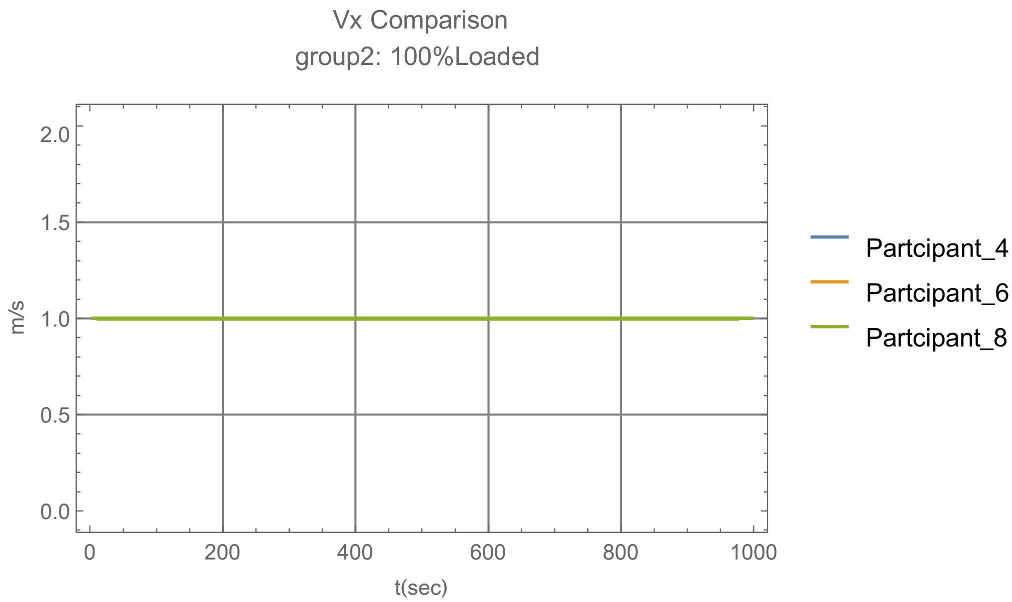


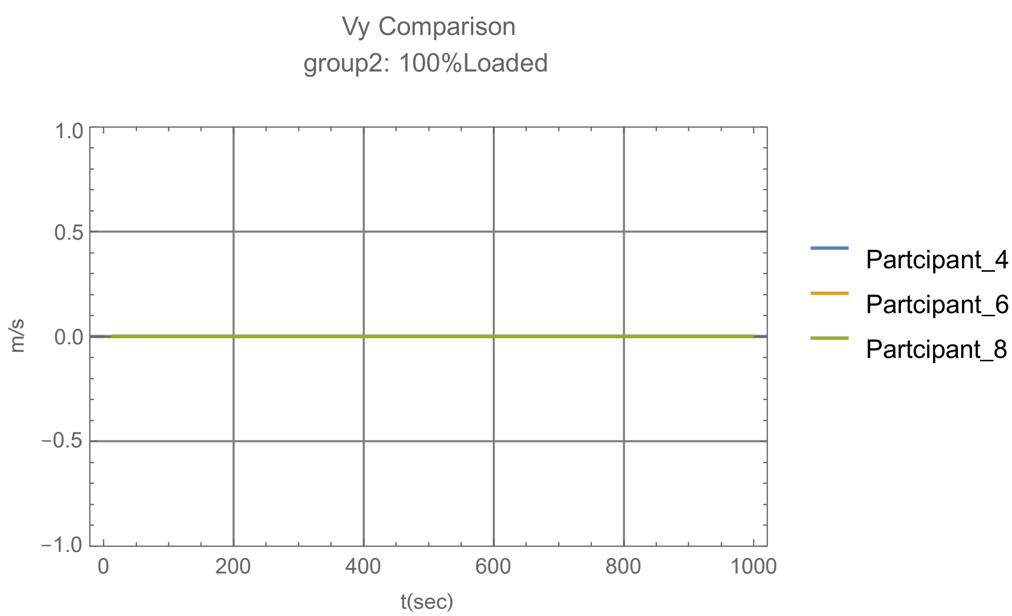
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Strobe History Image; strobe period 50 seconds

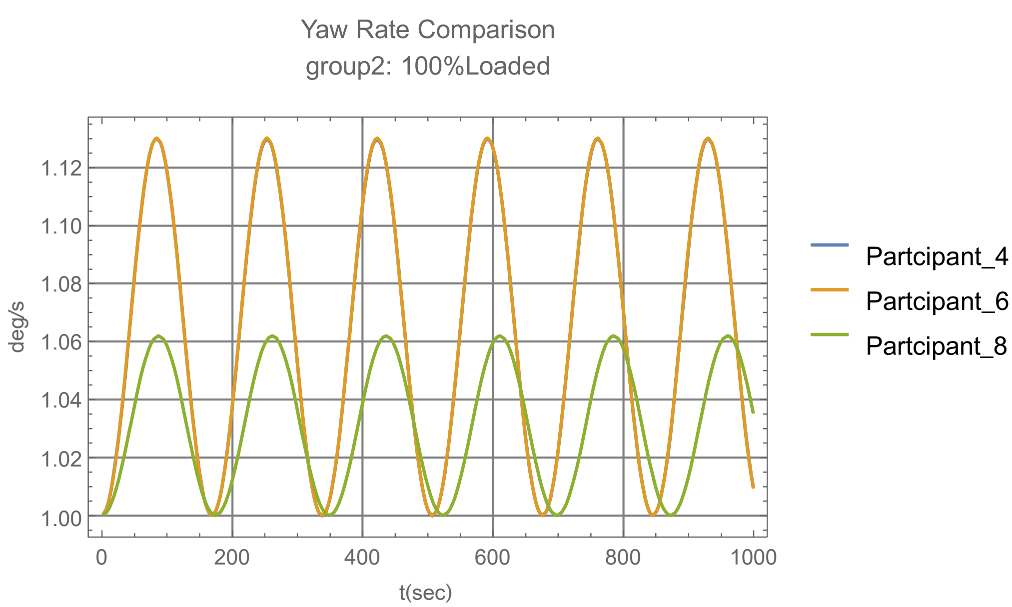



Rx Comparison
group2: 100% Loaded
meters
t (sec)
Partcipant_4
Partcipant_6
Partcipant_8

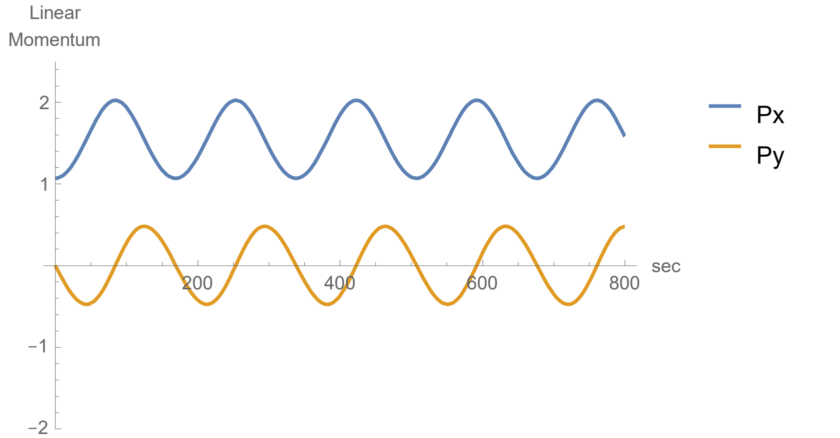

Ry Comparison
group2: 100% Loaded
meters
t (sec)
Partcipant_4
Partcipant_6
Partcipant_8


Vx Comparison
group2: 100%Loaded
m/s
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8

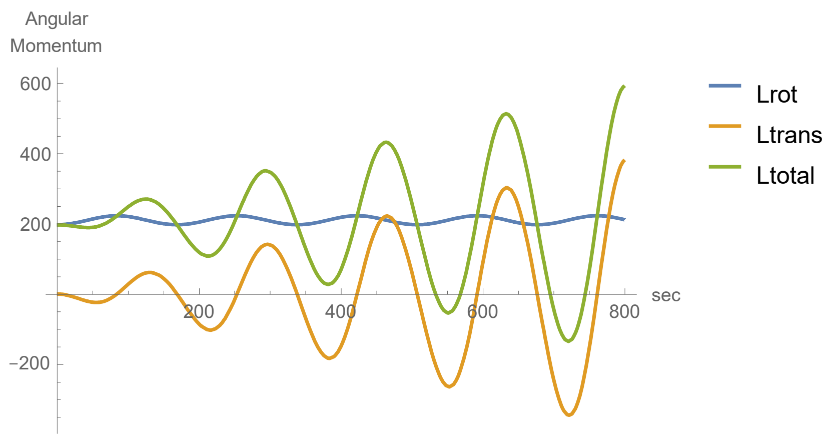

Vy Comparison
group2: 100%Loaded
m/s
1.0
0.5
0.0
−0.5
−1.0
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8


Yaw Rate Comparison
group2: 100%Loaded
deg/s
1.12
1.10
1.08
1.06
1.04
1.02
1.00
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8

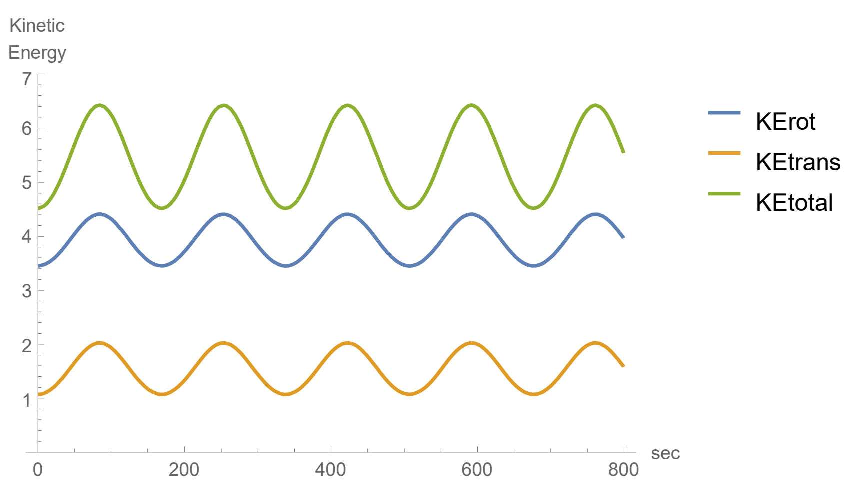
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Linear Momentum



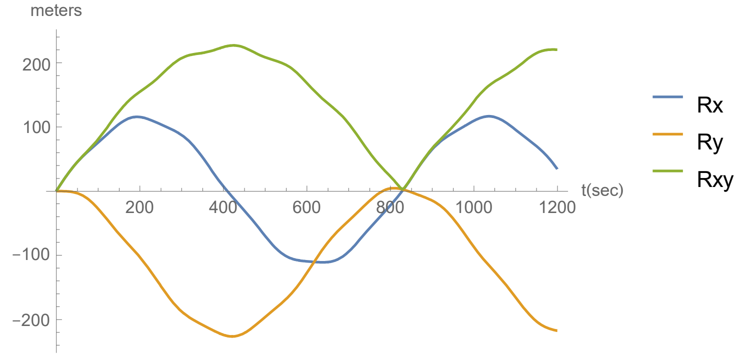
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Angular Momentum



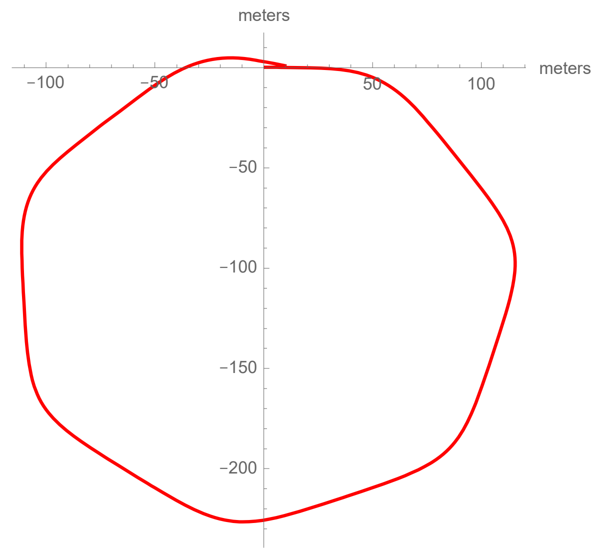
group2: 100%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Kinetic Energy



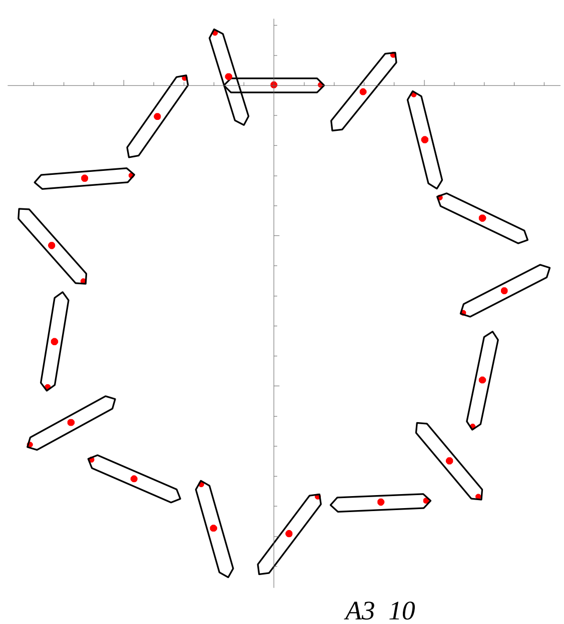
group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}

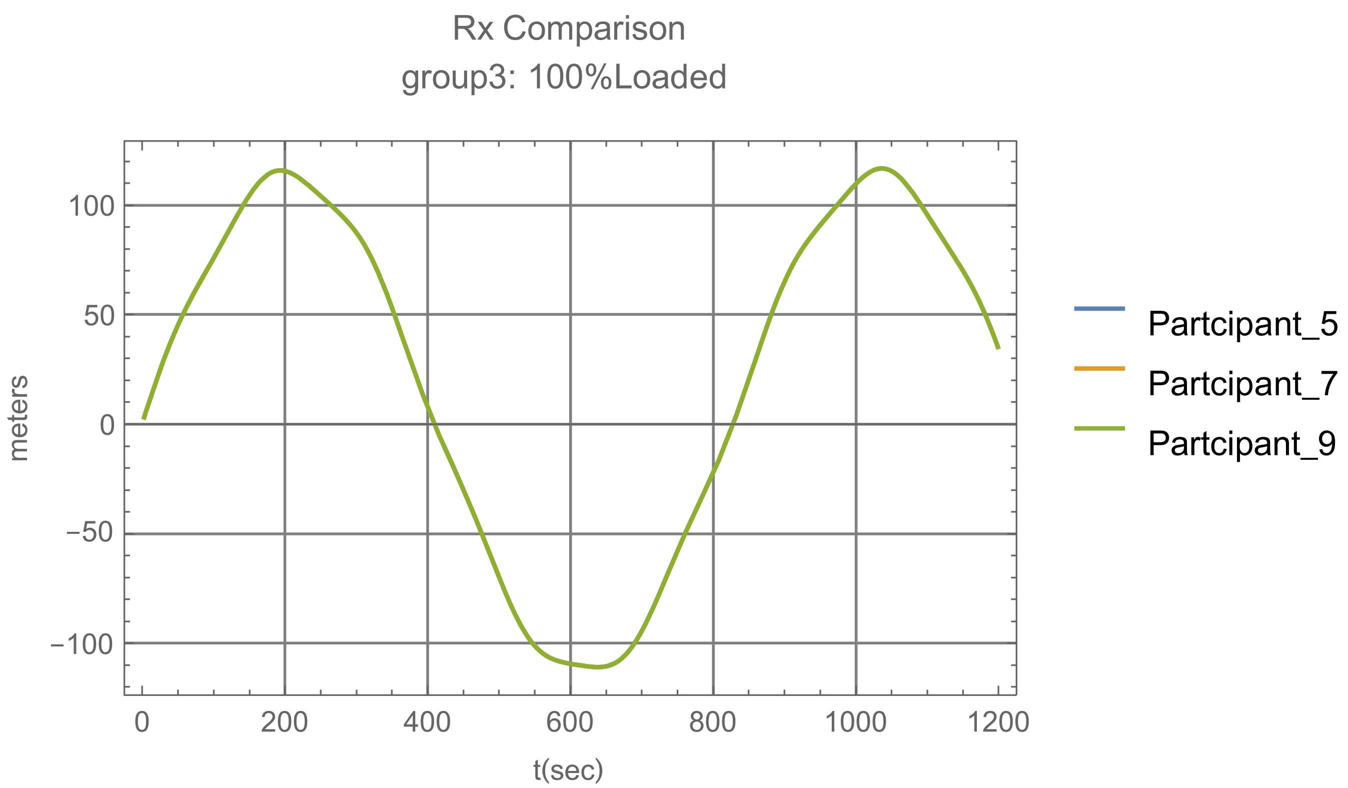


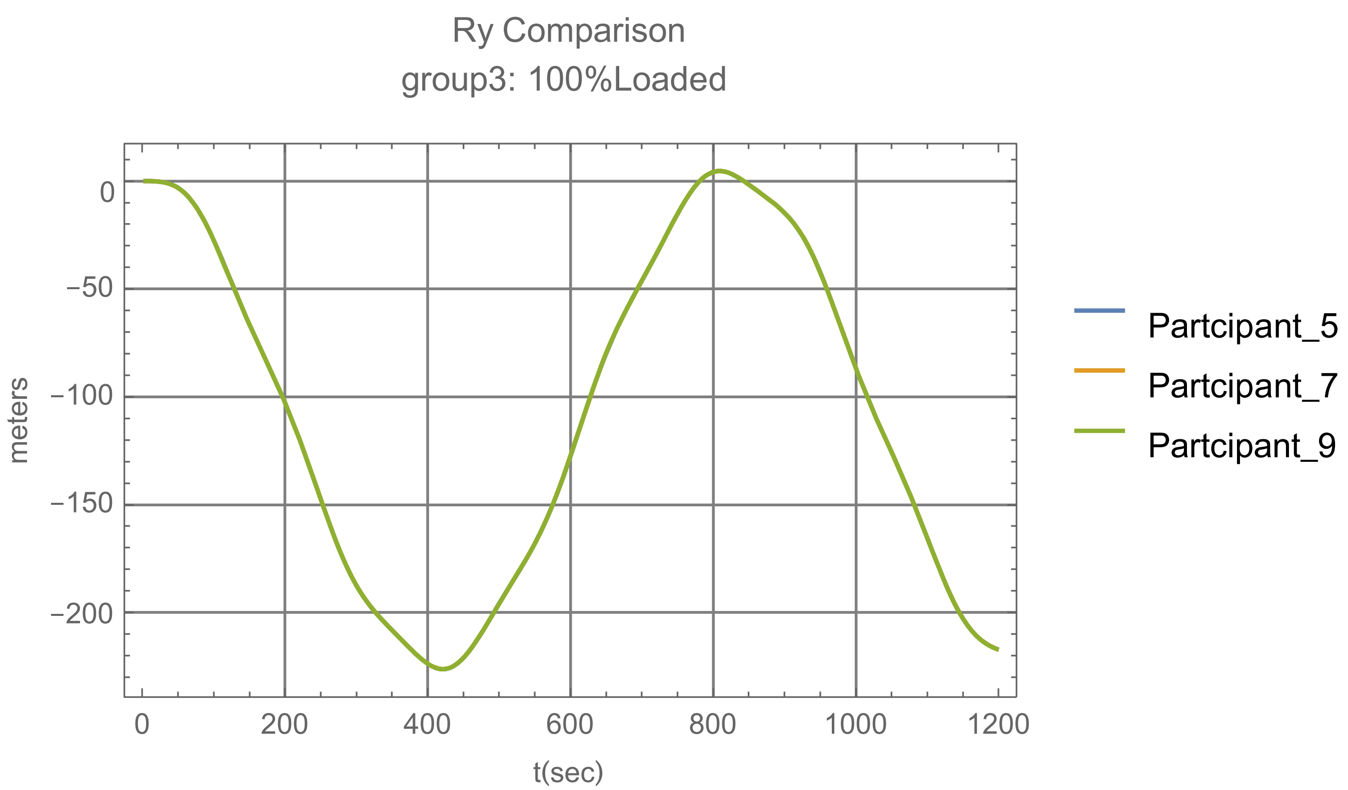
group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Vessel CG Track

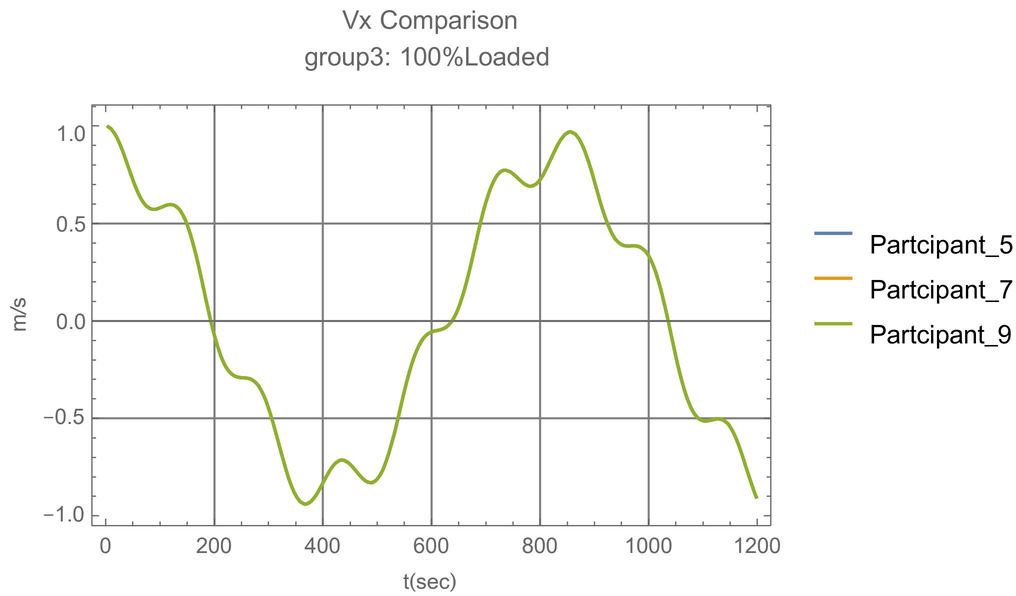


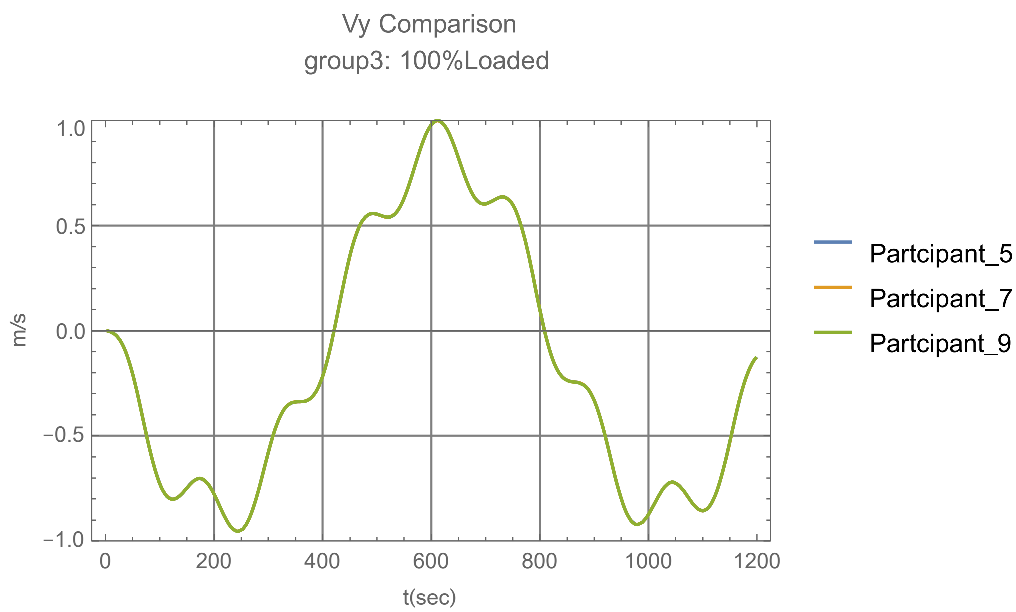
group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Strobe History Image; strobe period 50 seconds

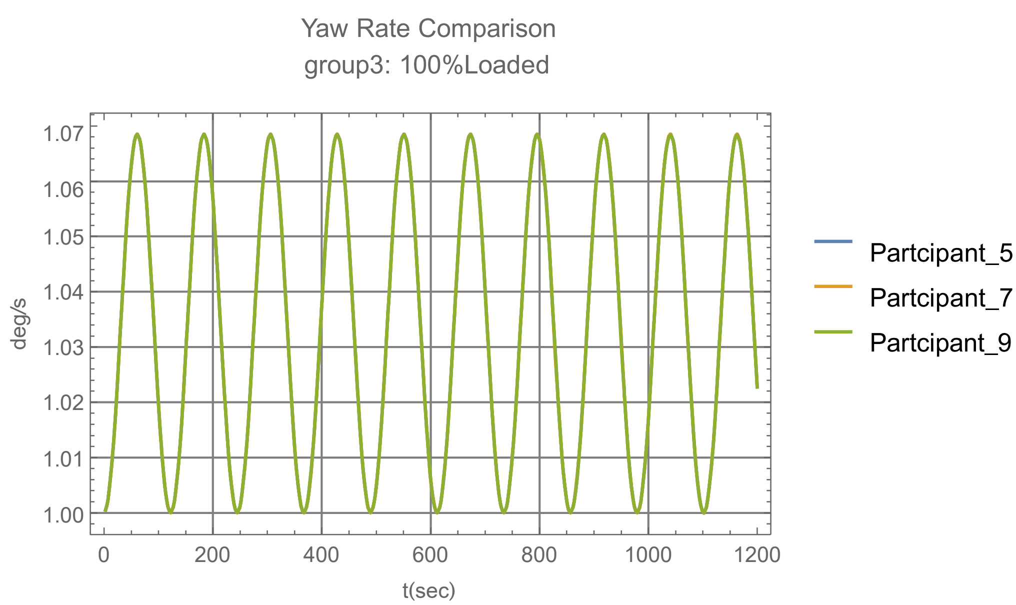



Rx Comparison
group3: 100%Loaded
meters
t(sec)
100
50
0
−50
−100
0
200
400
600
800
1000
1200
Partcipant_5
Partcipant_7
Partcipant_9

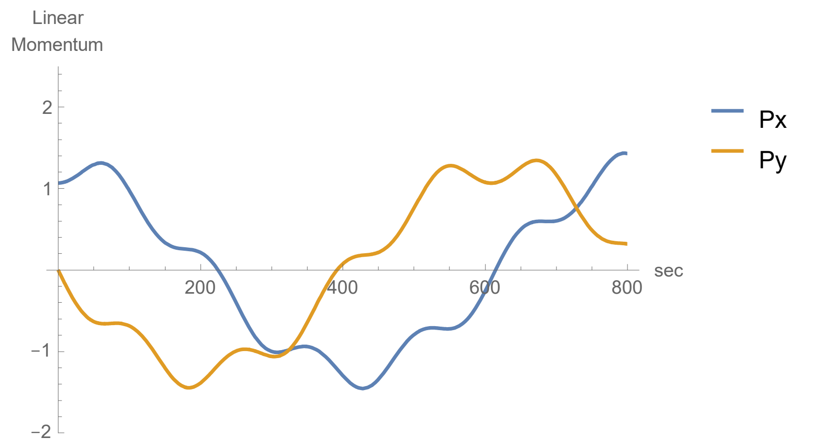

Ry Comparison
group3: 100%Loaded
meters
t(sec)
0
−50
−100
−150
−200
0
200
400
600
800
1000
1200
Partcipant_5
Partcipant_7
Partcipant_9


Vx Comparison
group3: 100%Loaded
m/s
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9

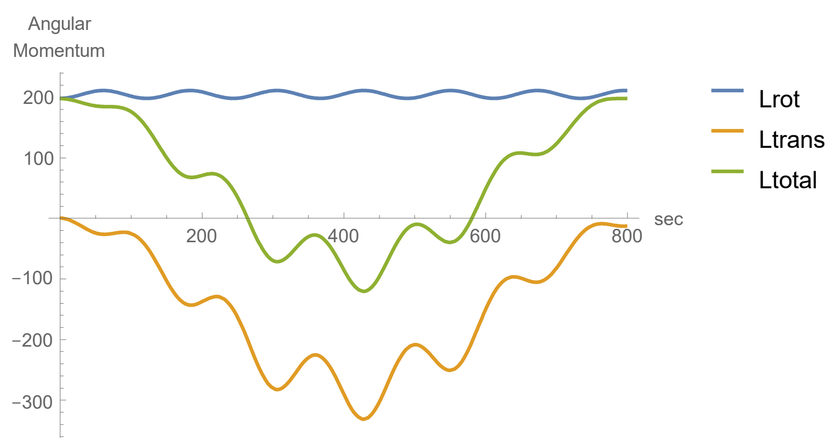

Vy Comparison
group3: 100%Loaded
m/s
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9


Yaw Rate Comparison
group3: 100%Loaded
deg/s
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9

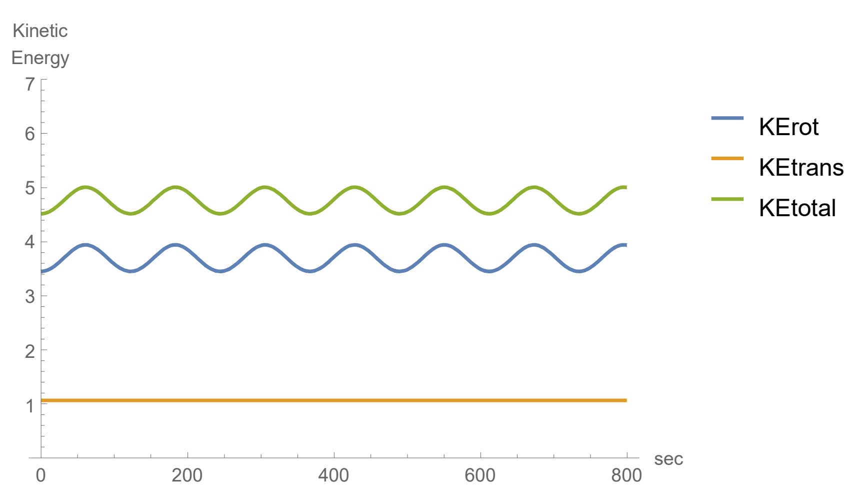
group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Linear Momentum



group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Angular Momentum



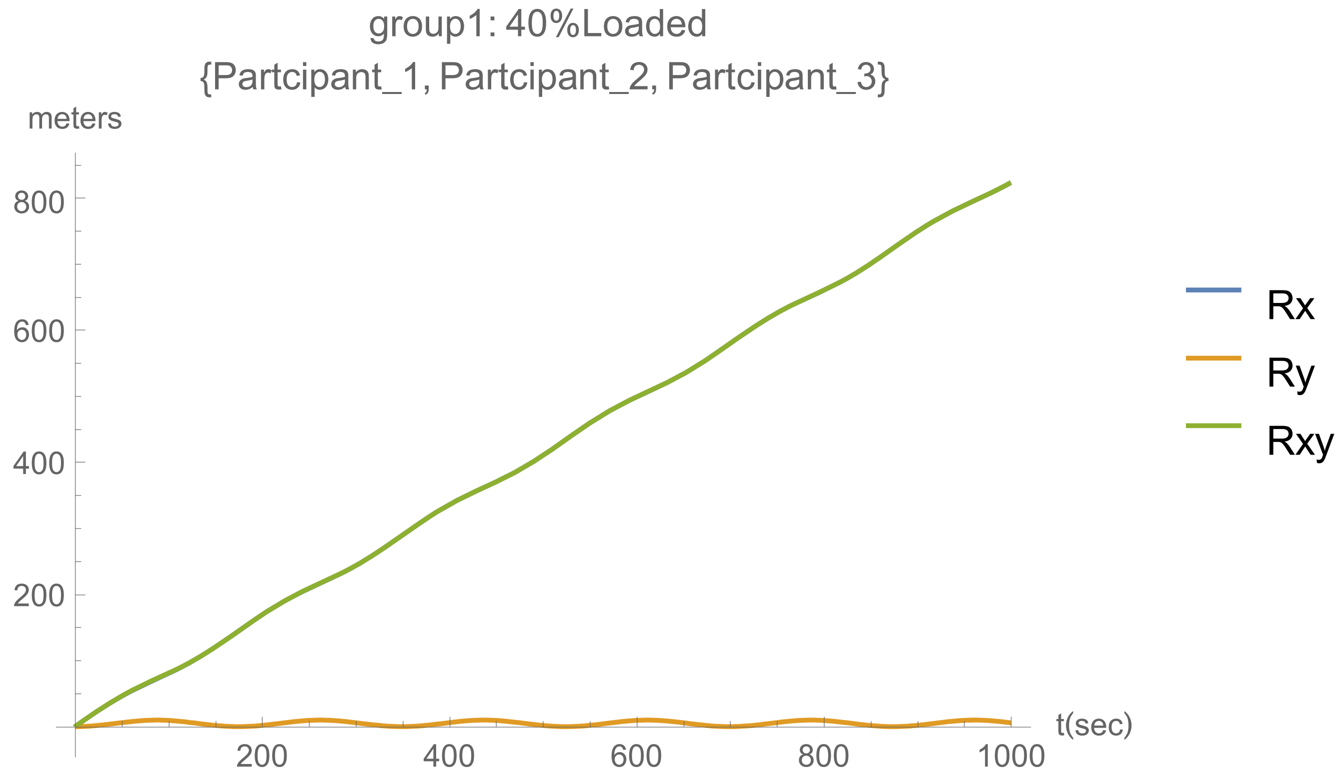
group3: 100%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Kinetic Energy

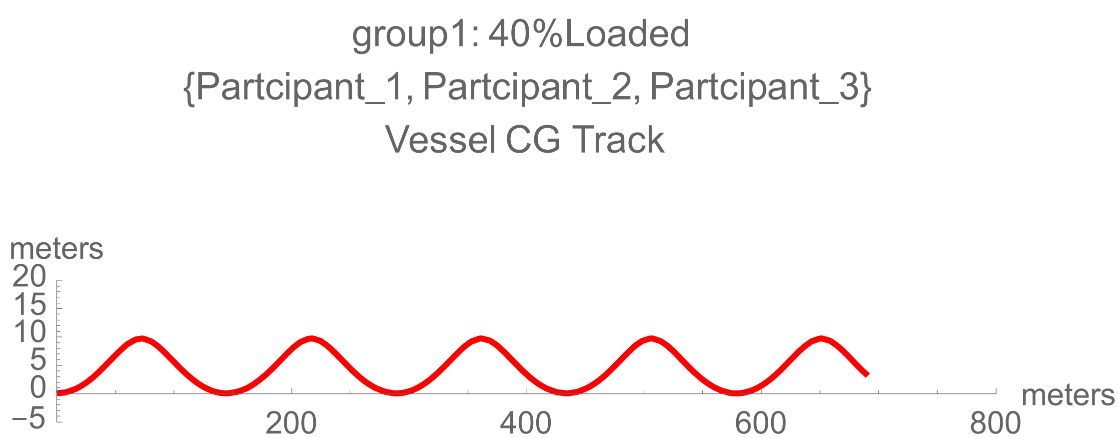


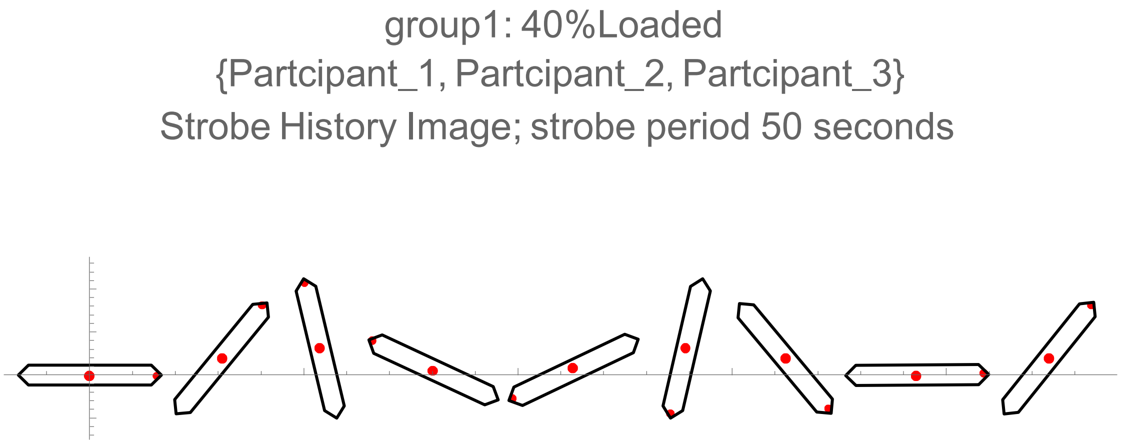
Appendix IV

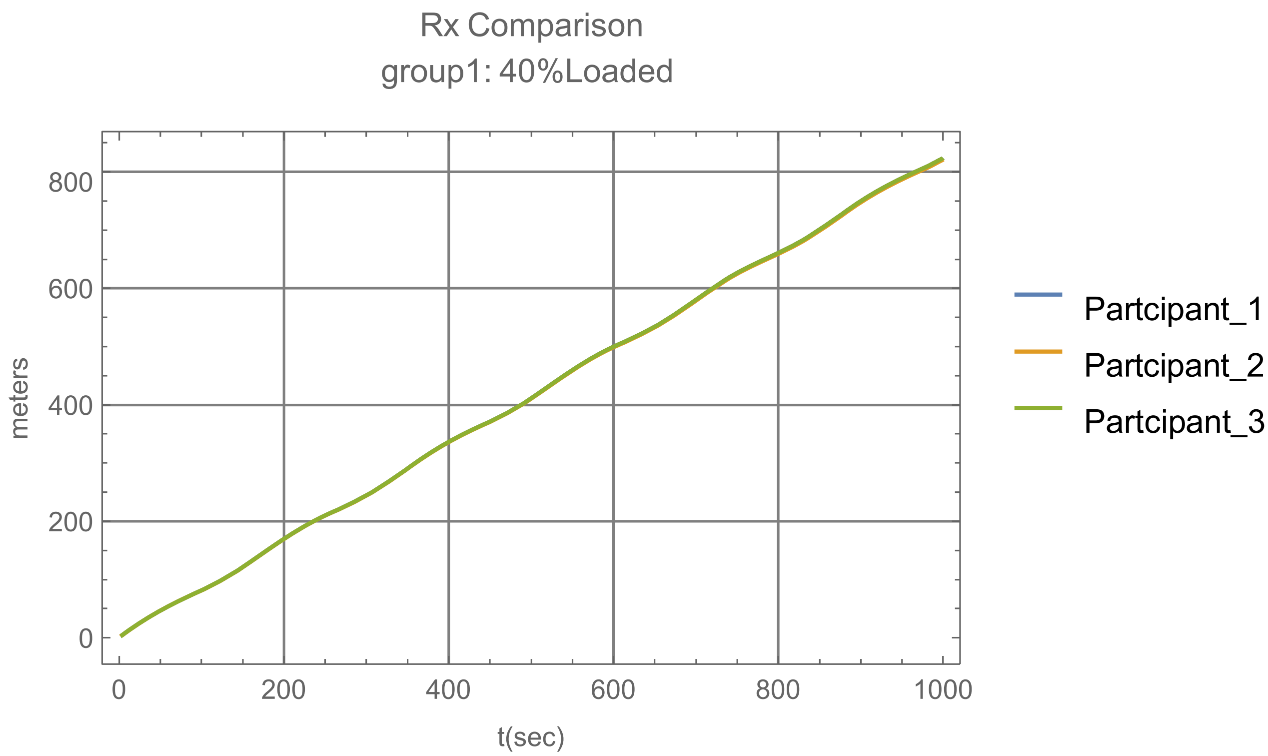
Per-Participant Graphical Summaries: 40% Load Case

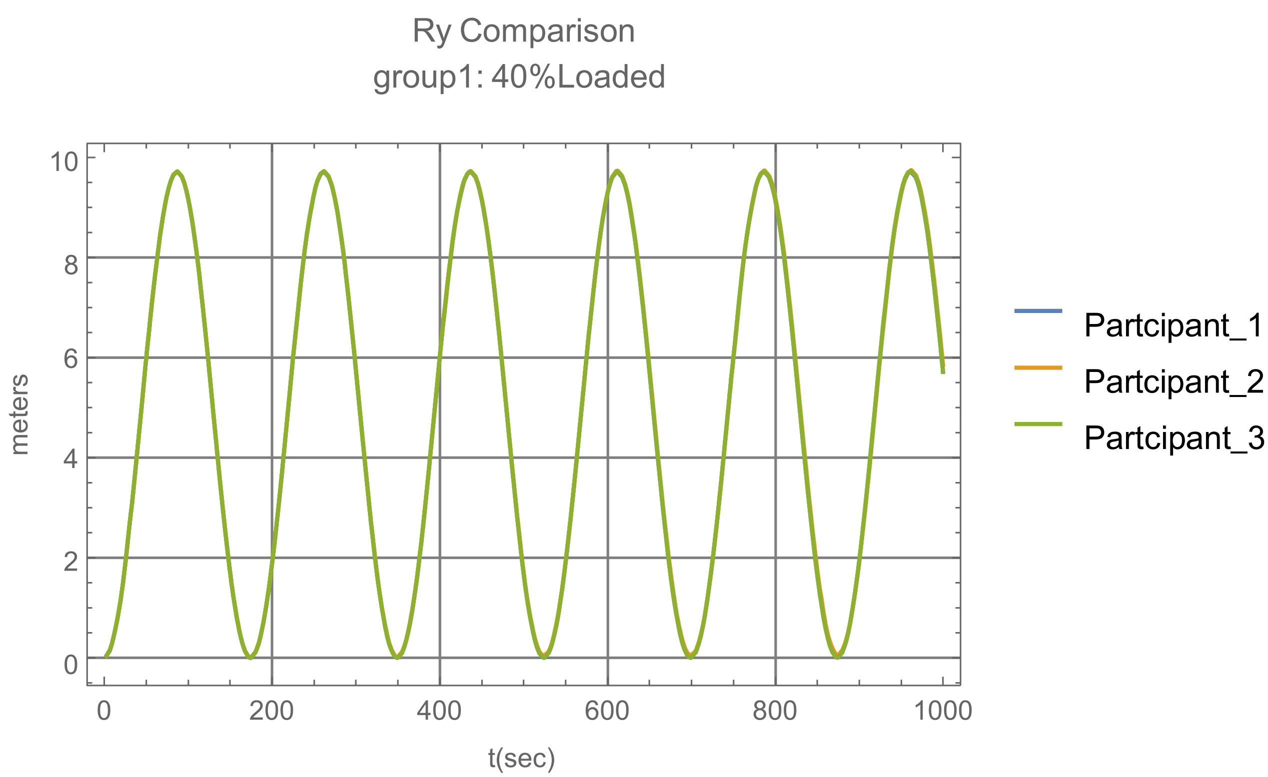
Visualizations of the vessel motions for each of the nine Participants are provided on the following pages. Fundamentally identical sets of data are combined, when possible.

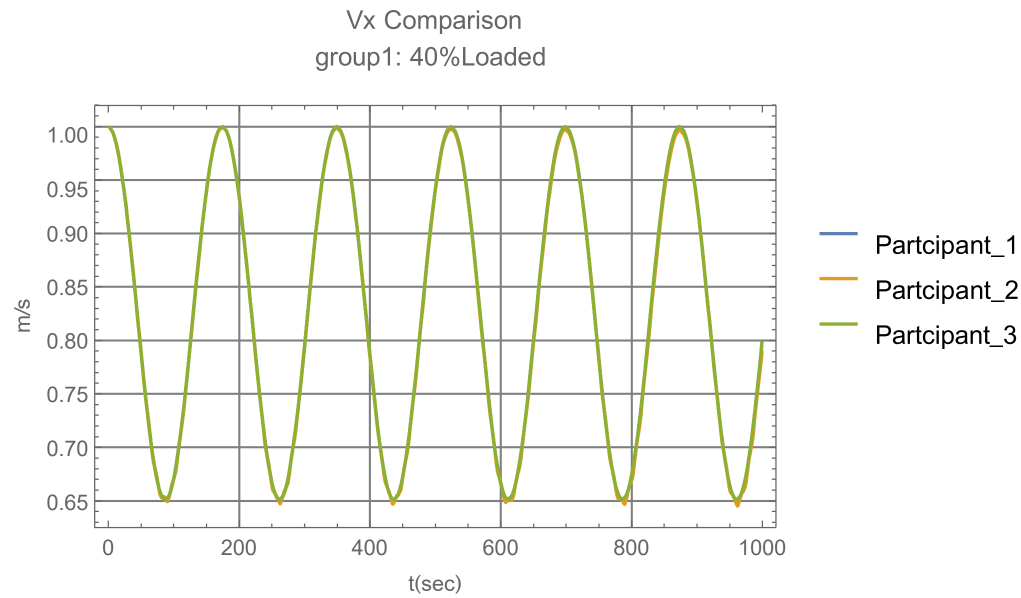

group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
meters
800
600
400
200
200
400
600
800
1000
t(sec)
Rx
Ry
Rxy

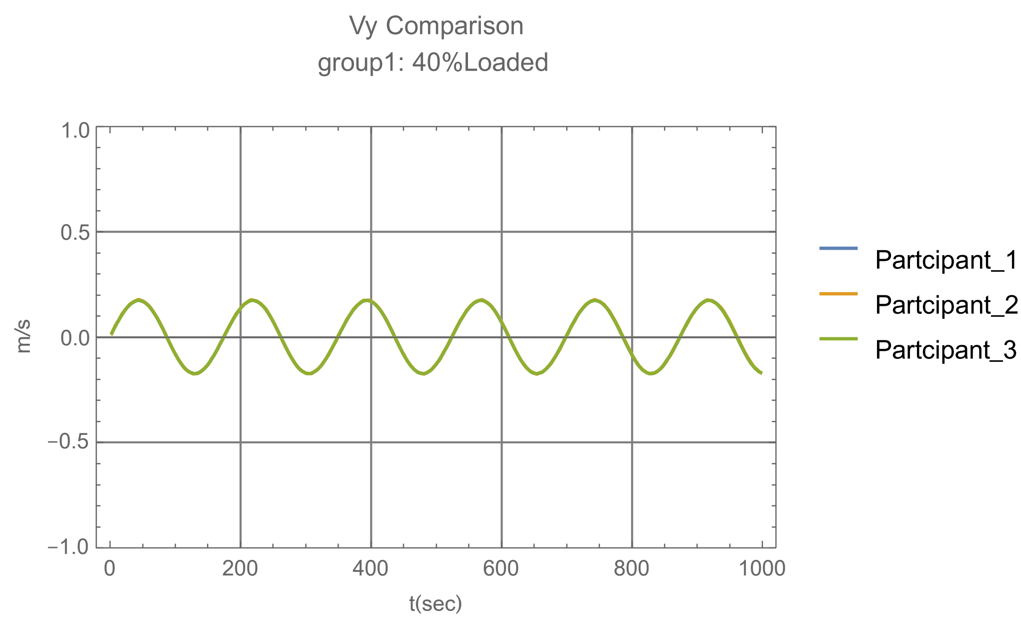

group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Vessel CG Track
meters
20
15
10
5
0
−5
200
400
600
800
meters

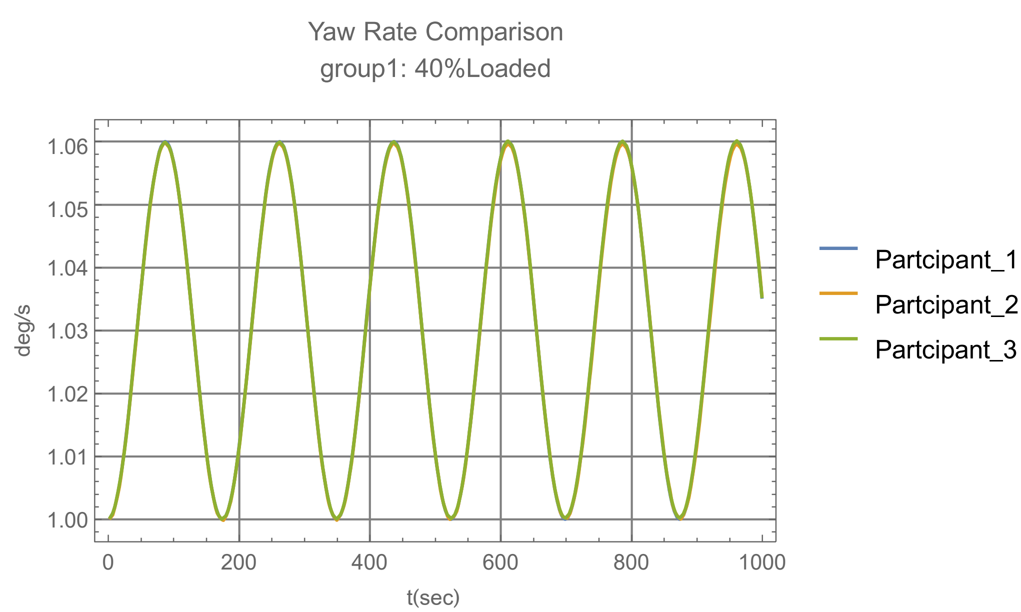

group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Strobe History Image; strobe period 50 seconds


Rx Comparison
group1: 40%Loaded
meters
0
200
400
600
800
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3

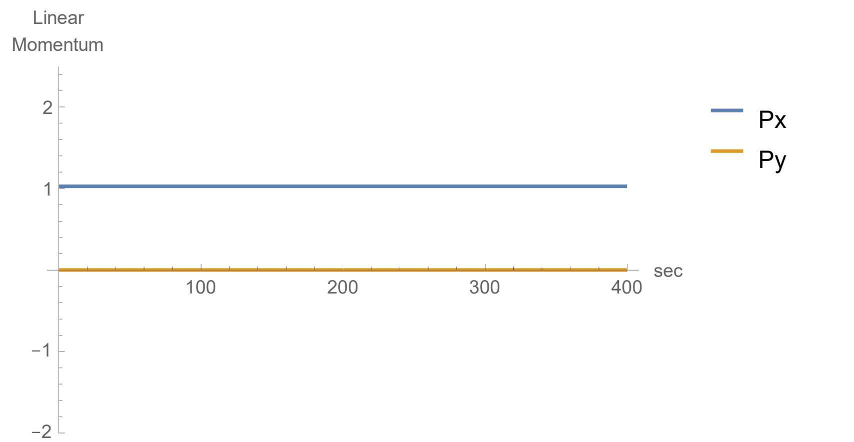

Ry Comparison
group1: 40%Loaded
meters
0
2
4
6
8
10
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3


Vx Comparison
group1: 40%Loaded
m/s
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3

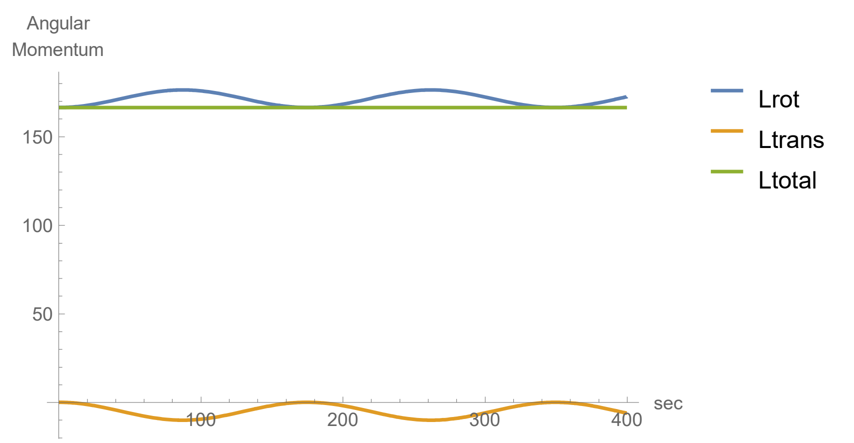

Vy Comparison
group1: 40%Loaded
m/s
1.0
0.5
0.0
−0.5
−1.0
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3


Yaw Rate Comparison
group1: 40%Loaded
deg/s
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0
200
400
600
800
1000
t(sec)
Partcipant_1
Partcipant_2
Partcipant_3

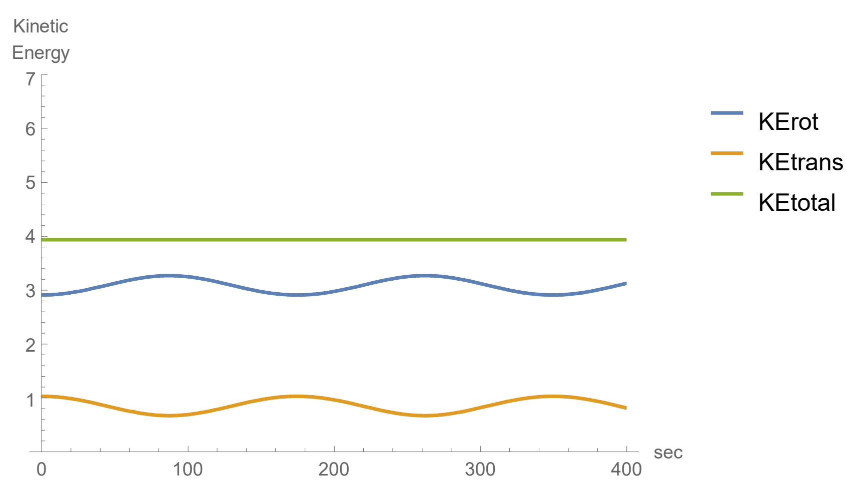
group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Linear Momentum

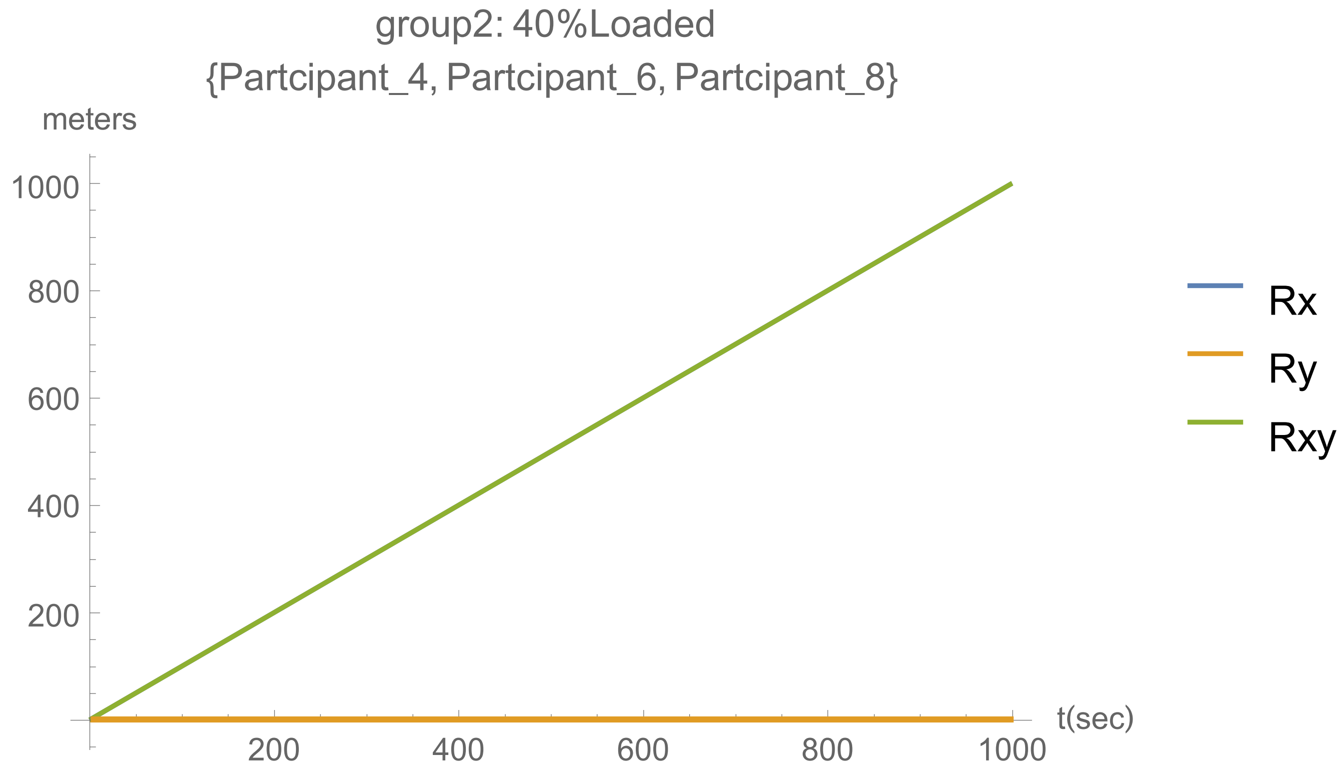


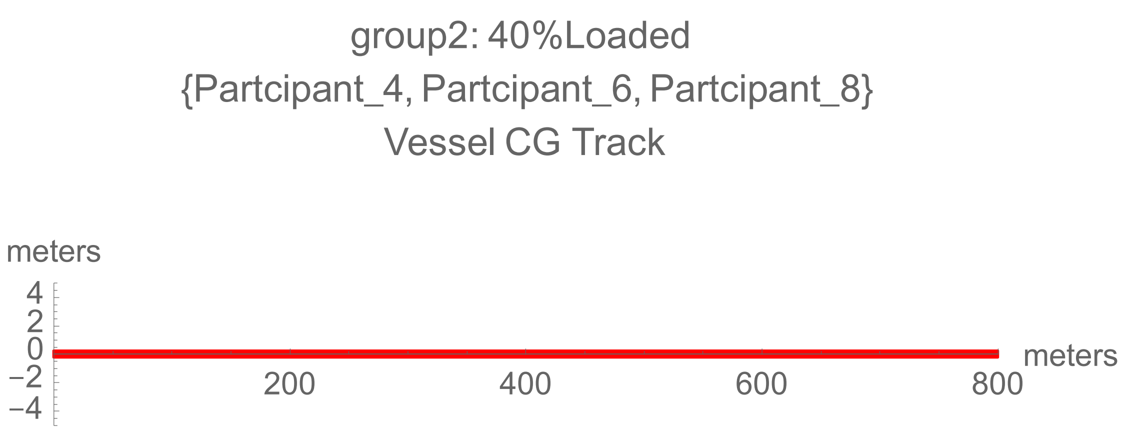
group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Angular Momentum

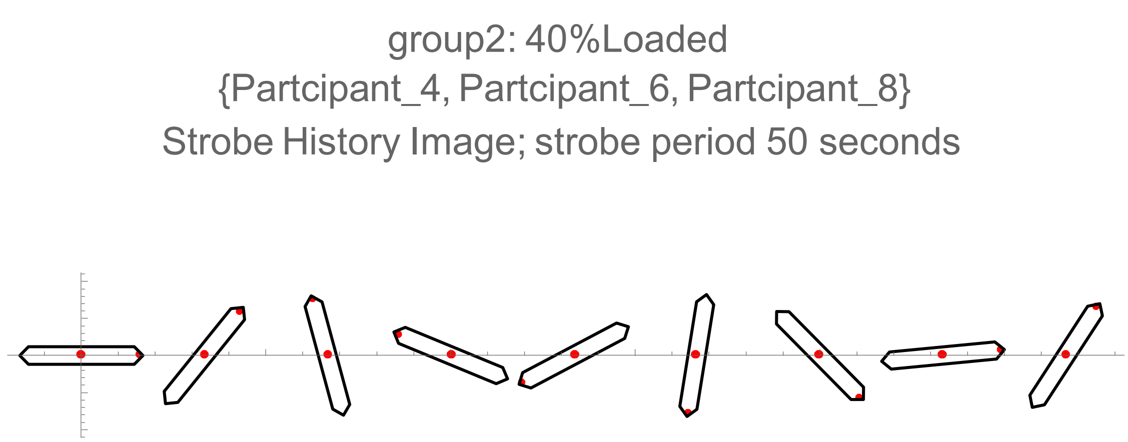


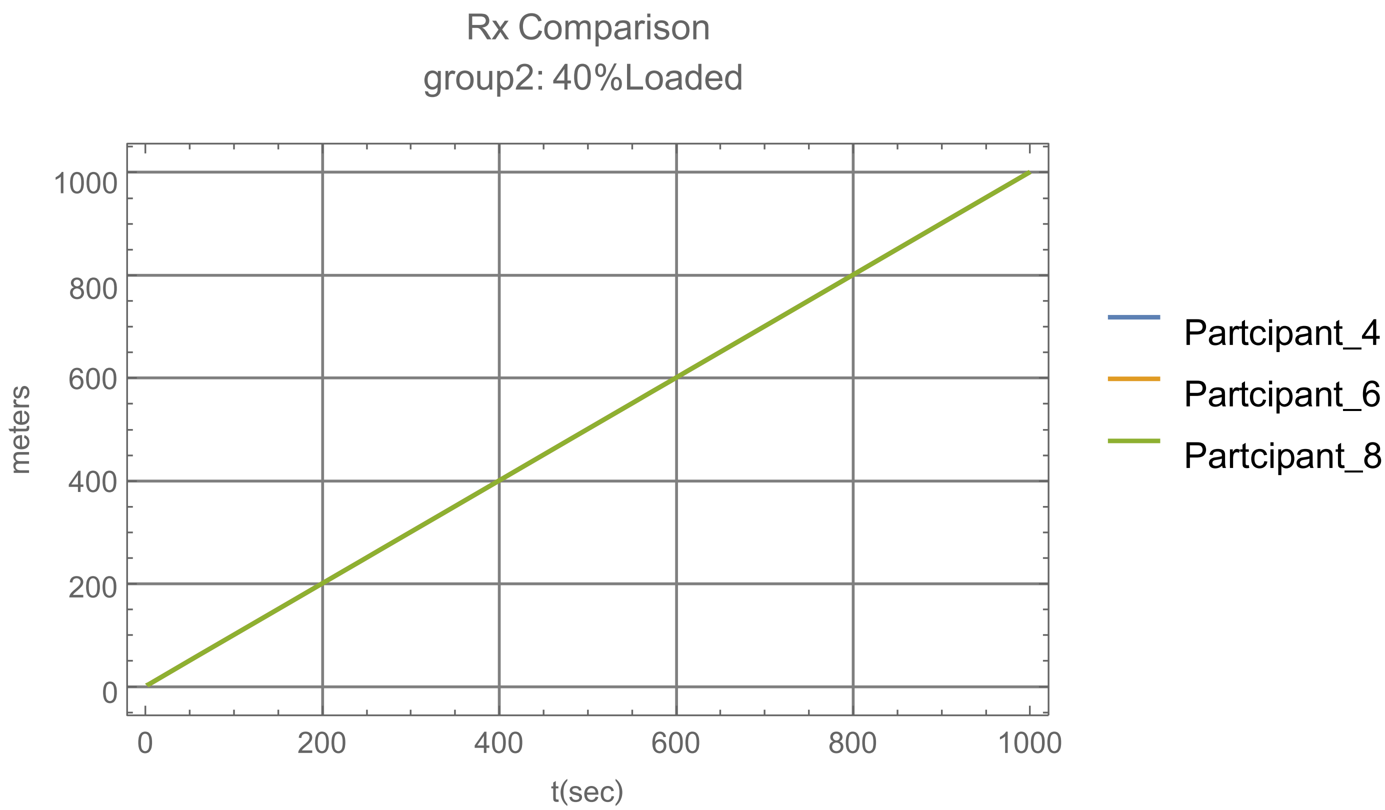
group1: 40%Loaded
{Partcipant_1, Partcipant_2, Partcipant_3}
Scaled Kinetic Energy



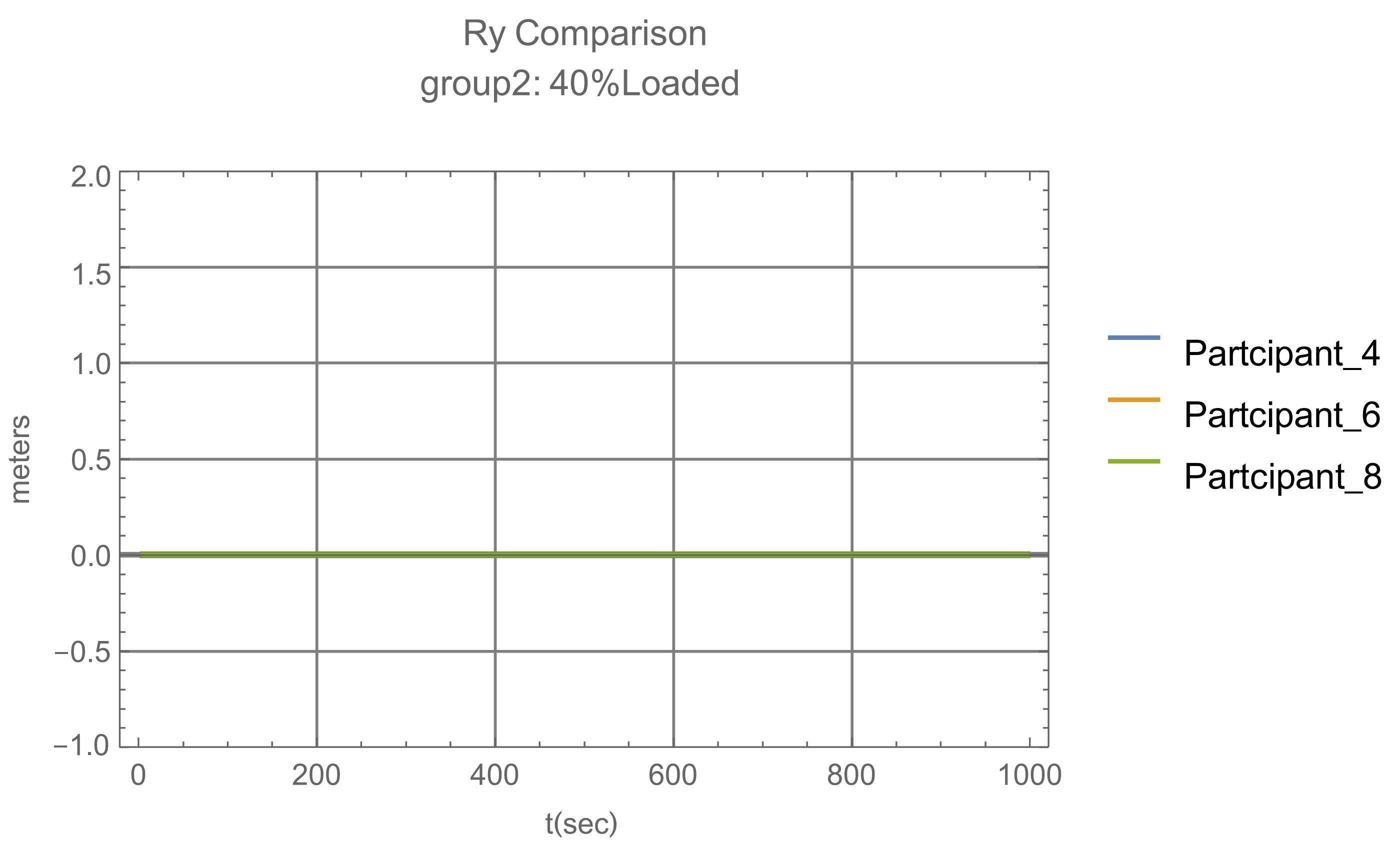

group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
meters
1000
800
600
400
200
200
400
600
800
1000
t(sec)
Rx
Ry
Rxy


group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Vessel CG Track
meters
4
2
0
−2
−4
200
400
600
800
meters

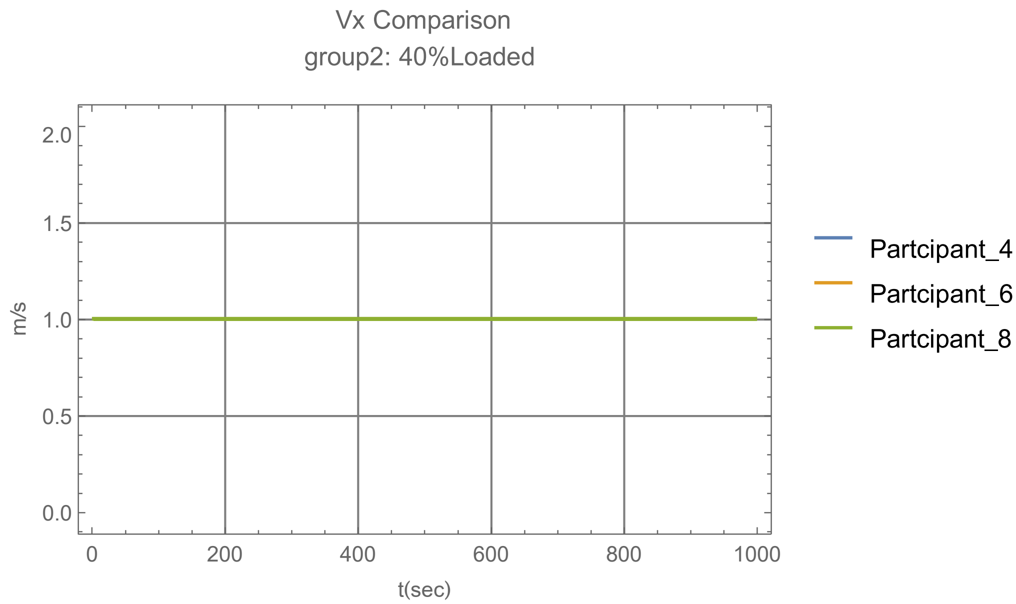

group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Strobe History Image; strobe period 50 seconds



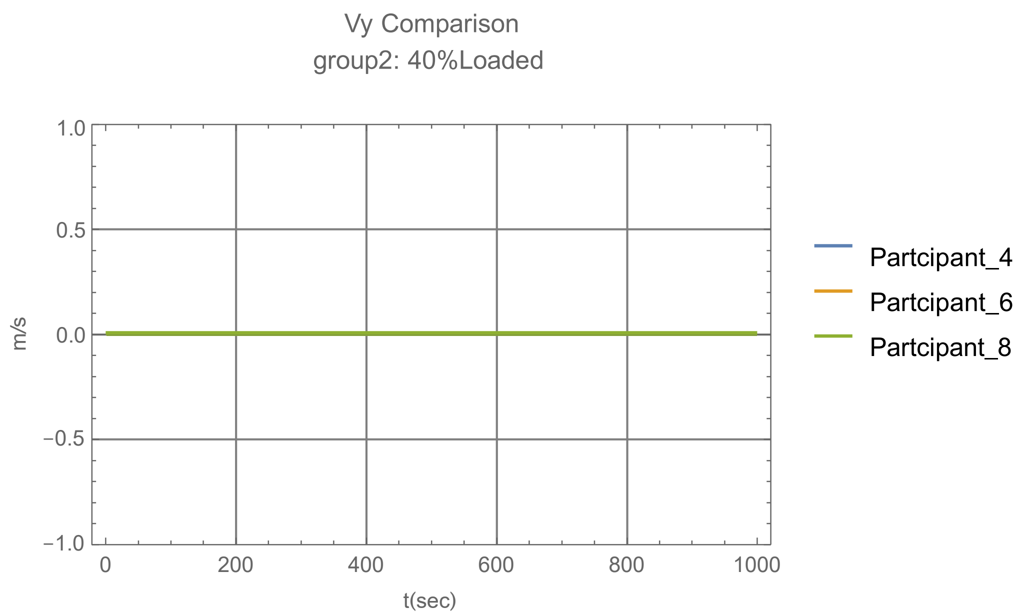
Rx Comparison
group2: 40%Loaded
meters
t(sec)
0
200
400
600
800
1000
Partcipant_4
Partcipant_6
Partcipant_8



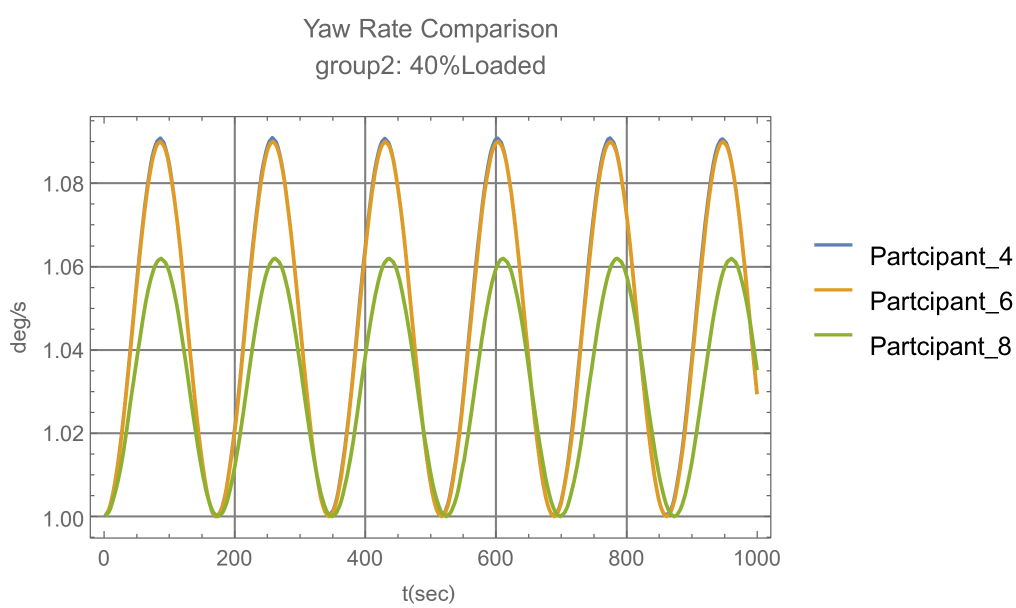
Ry Comparison
group2: 40%Loaded
meters
t(sec)
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
0
200
400
600
800
1000
Partcipant_4
Partcipant_6
Partcipant_8



Vx Comparison
group2: 40%Loaded
m/s
2.0
1.5
1.0
0.5
0.0
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8

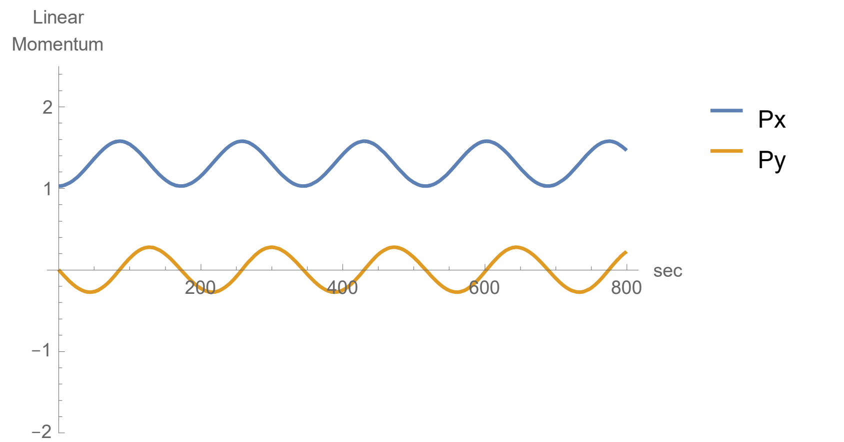


Vy Comparison
group2: 40%Loaded
m/s
1.0
0.5
0.0
−0.5
−1.0
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8

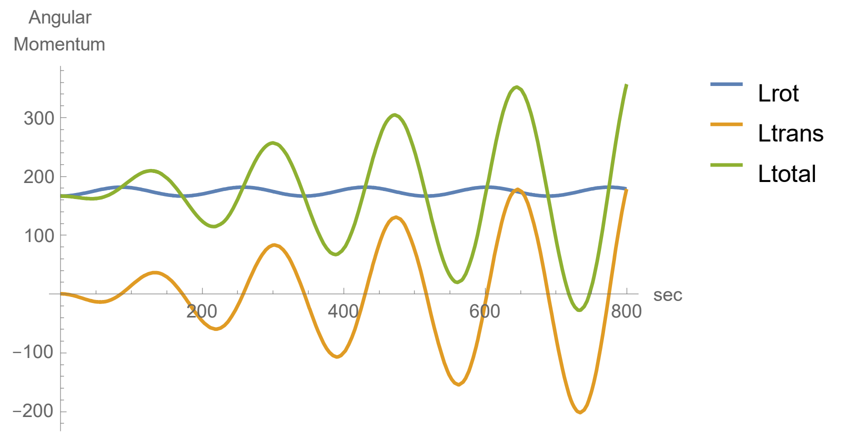


Yaw Rate Comparison
group2: 40%Loaded
deg/s
1.08
1.06
1.04
1.02
1.00
0
200
400
600
800
1000
t(sec)
Partcipant_4
Partcipant_6
Partcipant_8

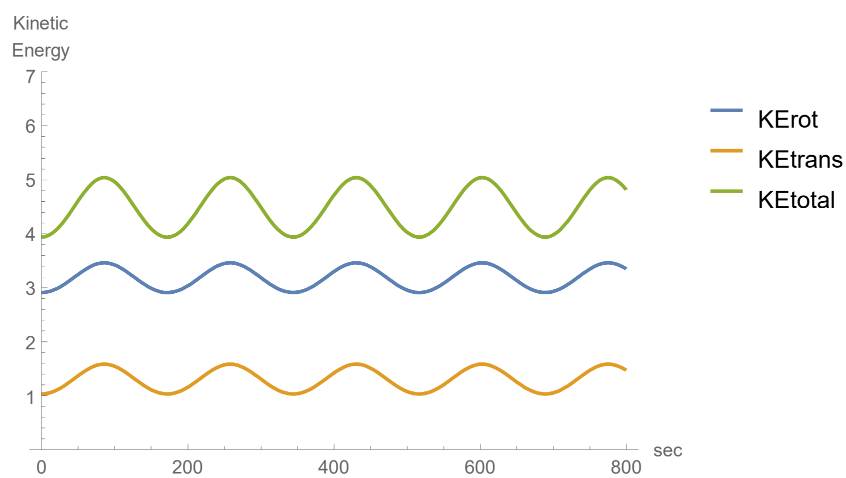
group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Linear Momentum



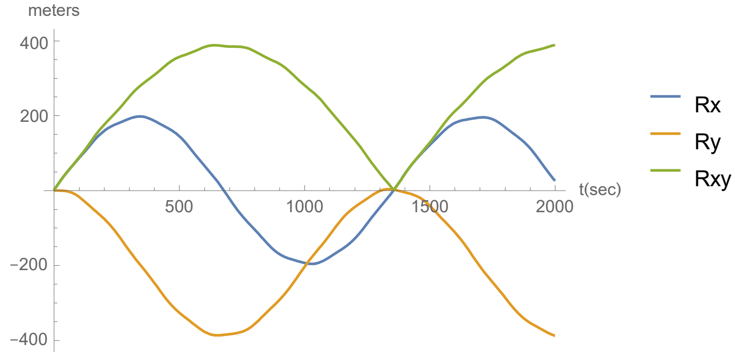
group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Angular Momentum



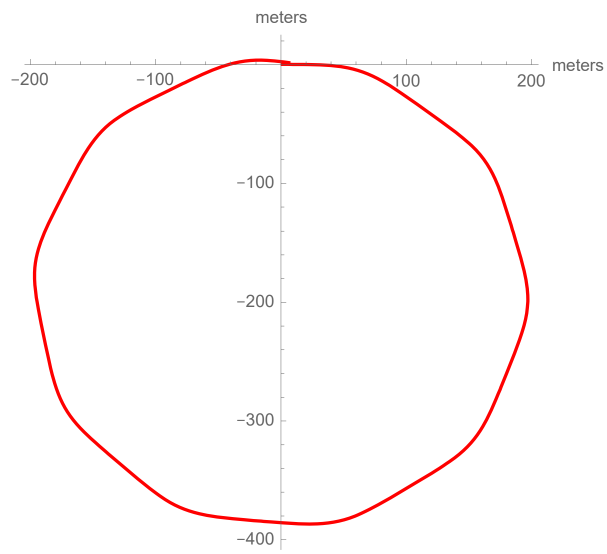
group2: 40%Loaded
{Partcipant_4, Partcipant_6, Partcipant_8}
Scaled Kinetic Energy



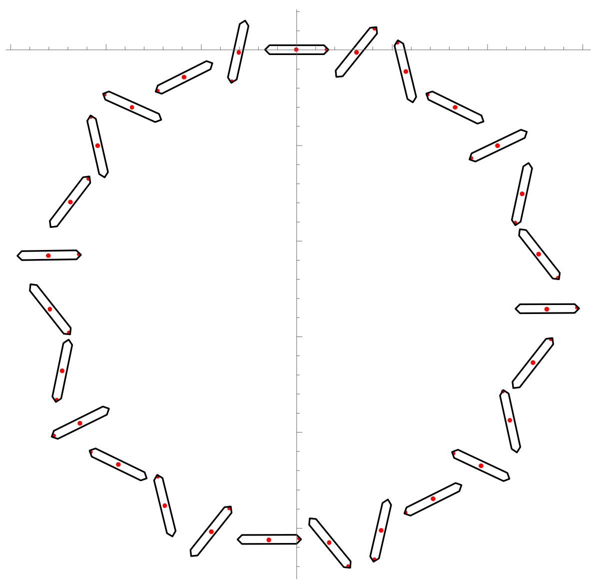
group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}

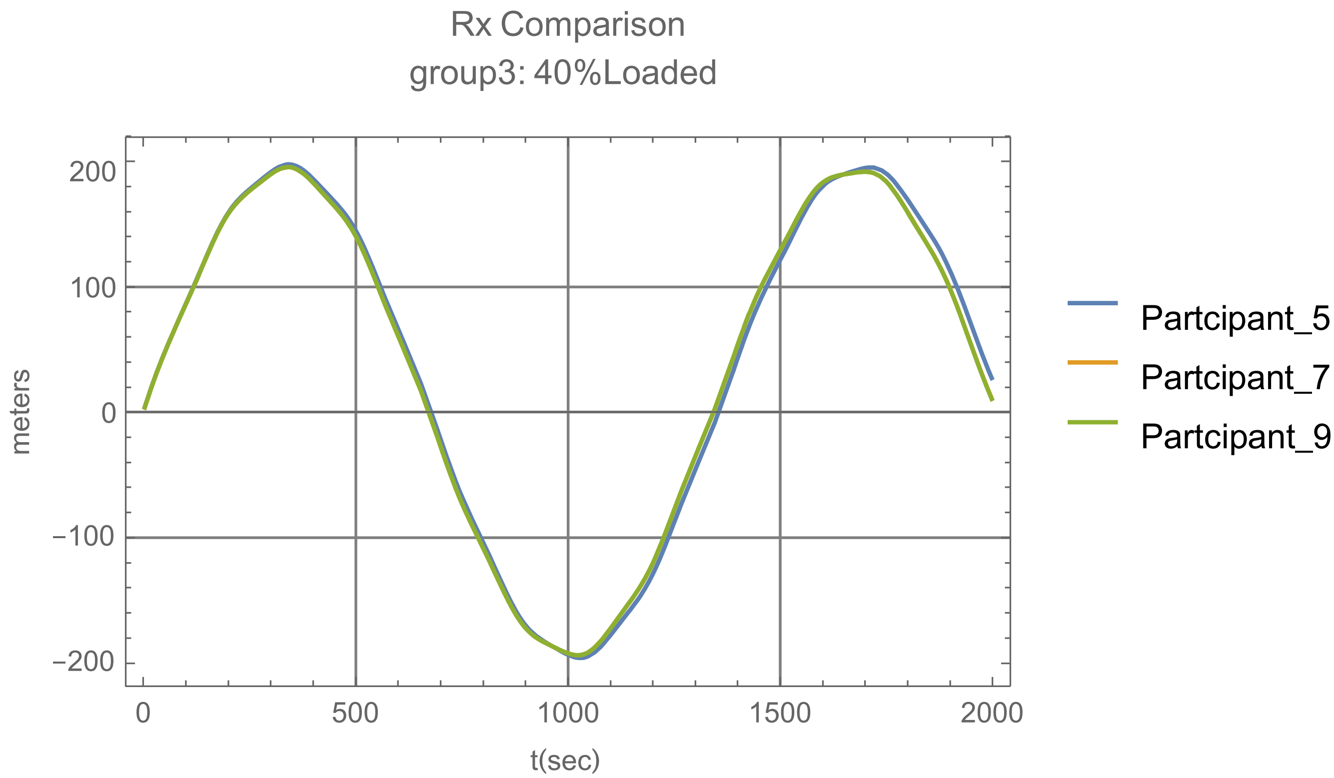


group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Vessel CG Track

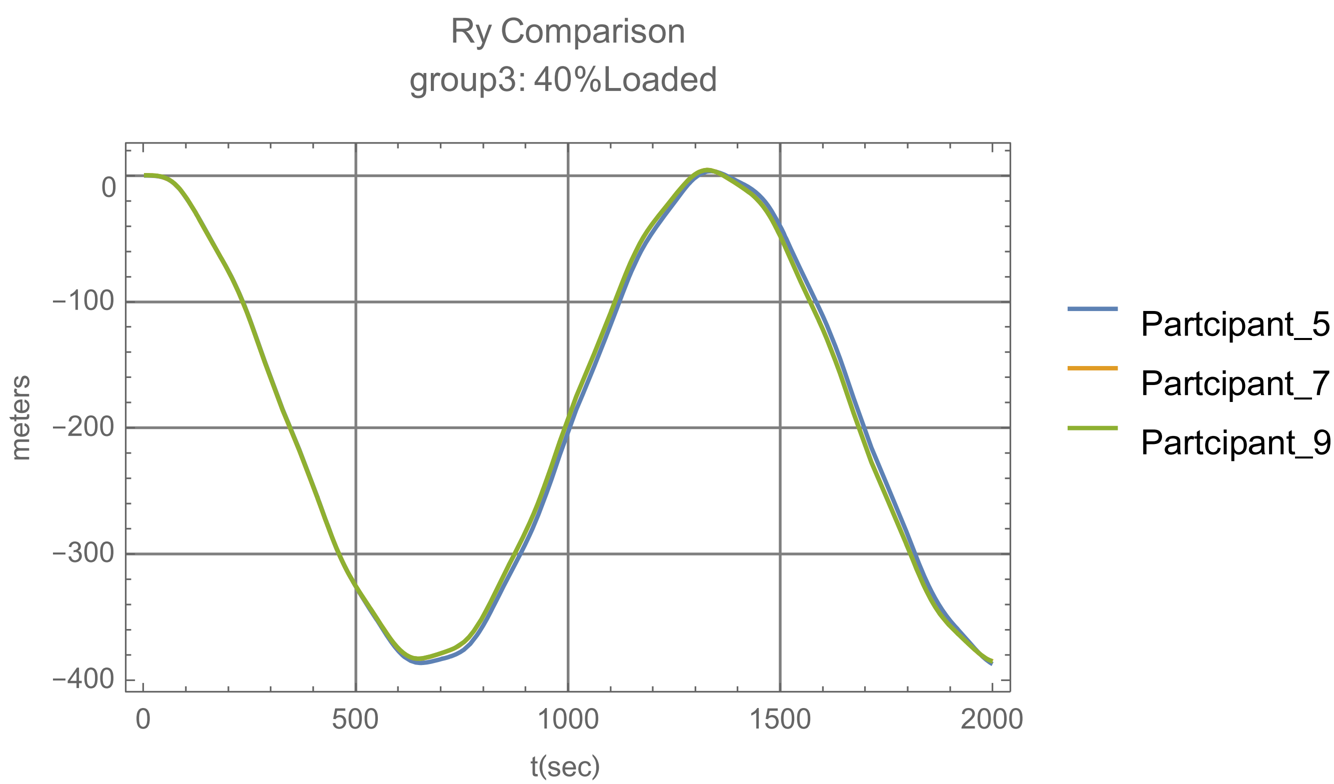


group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Strobe History Image; strobe period 50 seconds

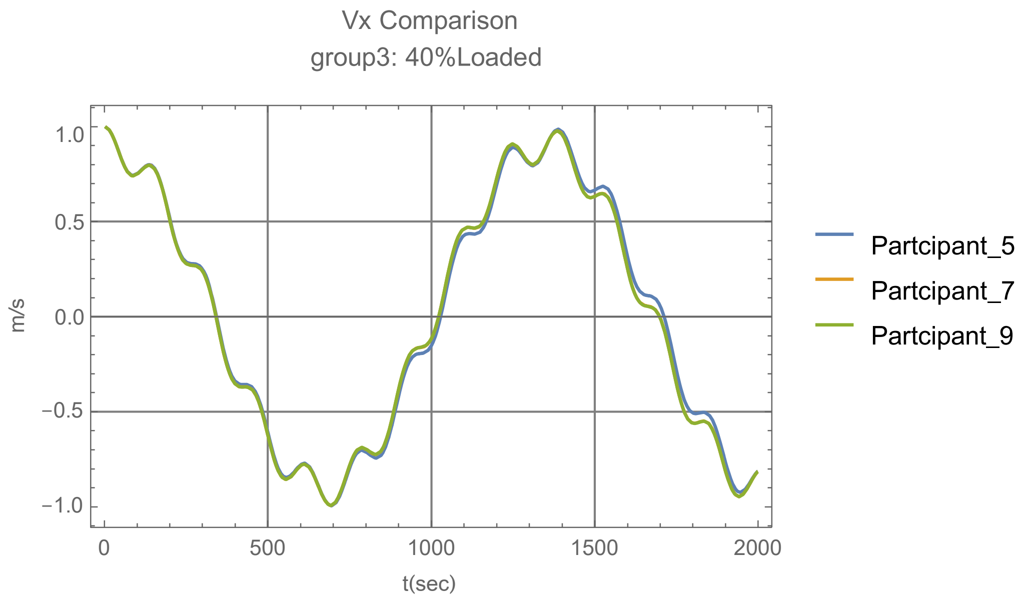


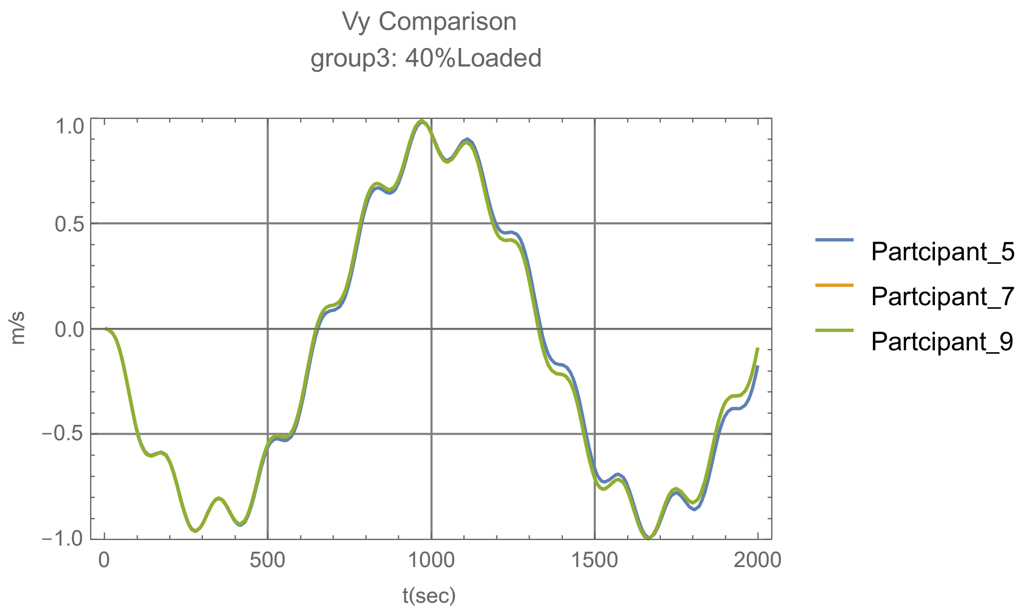


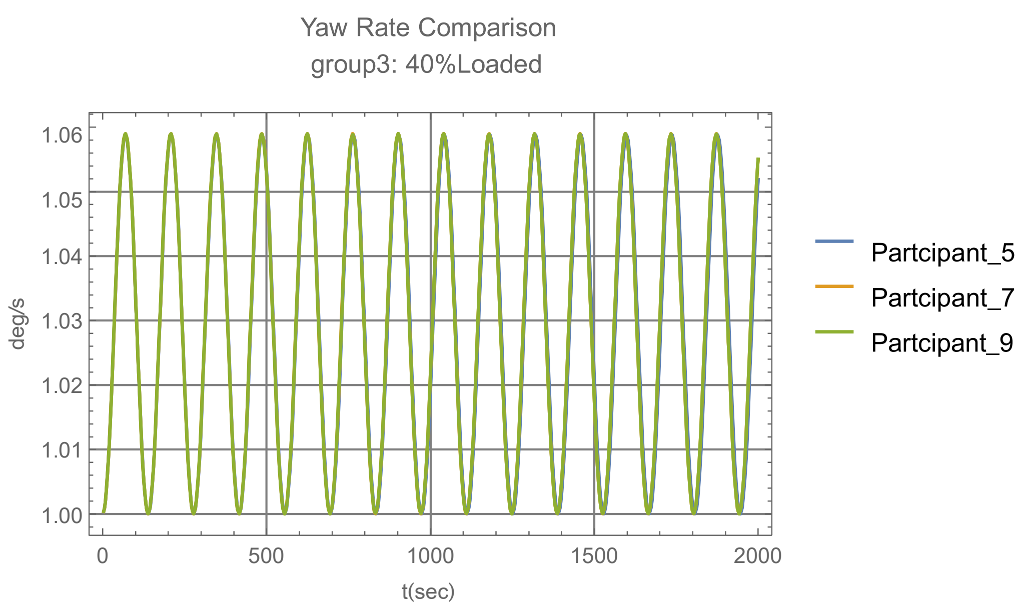
Rx Comparison
group3: 40%Loaded
200
100
0
−100
−200
meters
0
500
1000
1500
2000
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9



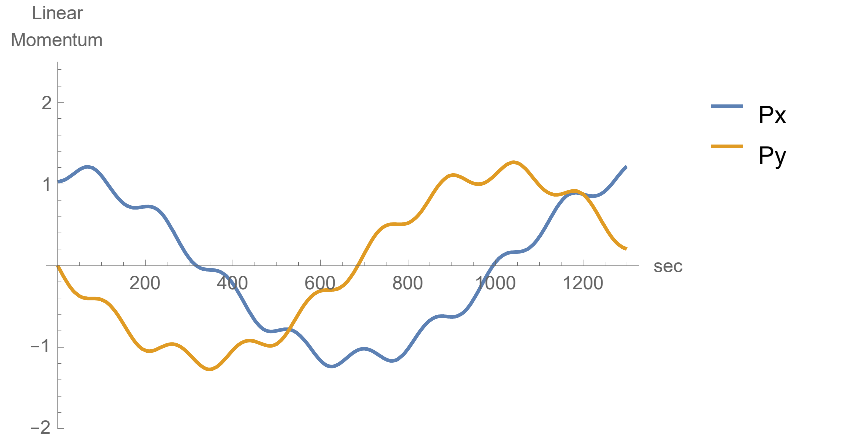
Ry Comparison
group3: 40%Loaded
0
−100
−200
−300
−400
meters
0
500
1000
1500
2000
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9


Vx Comparison
group3: 40%Loaded
m/s
1.0
0.5
0.0
−0.5
−1.0
0
500
1000
1500
2000
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9

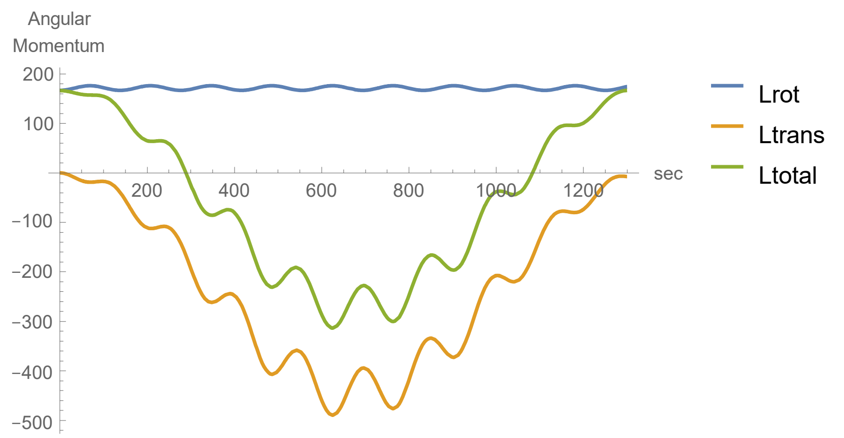

Vy Comparison
group3: 40%Loaded
m/s
1.0
0.5
0.0
−0.5
−1.0
0
500
1000
1500
2000
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9


Yaw Rate Comparison
group3: 40%Loaded
deg/s
1.06
1.05
1.04
1.03
1.02
1.01
1.00
0
500
1000
1500
2000
t(sec)
Partcipant_5
Partcipant_7
Partcipant_9

group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Linear Momentum



group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Angular Momentum



group3: 40%Loaded
{Partcipant_5, Partcipant_7, Partcipant_9}
Scaled Kinetic Energy