HIGH FIDELITY SIMULATION MODEL OF AN AERIAL REFUELING BOOM AND RECEPTACLE

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Abstract

Aerial refueling is considered to be a promising approach to reduce fuel burn and thus CO2 emissions of civil commercial aviation. Within a European research project it shall be evaluated if an aerial refueling maneuver can comply with civil airworthiness and safety standards. To substantiate this, detailed simulations are required. This paper presents a high fidelity aerial refueling boom model for simulation and boom controller design in MATLAB/SIMULINK. The boom is assembled from point masses and pipes, which are considered rigid bodies with individual inertia tensors. Instead of manually deriving equations of motion of the multi-body system (e.g. using the Newton-Euler method), the commercial SimMechanics Simulink toolbox is utilized, whereby still maintaining auto-code and real-time capability. To enable the simulation of a complete aerial refueling maneuver, a receptacle model is introduced and methods are described to take the interaction between the boom nozzle and the receptacle into account, including guidance of the boom tip towards the receptacle and constraint forces acting while the boom tip is coupled with the receptacle.

1. INTRODUCTION

Civil aviation has shown a robust growth over the previous decades with no end in sight. Despite significant improvements in aircraft and engines technology, the greenhouse gas emissions from international aviation however have increased by more than 4% per year [1]. Current targets set for emissions from aviation are the stabilization of net CO2 emissions from aviation from 2020 onward, and to reduce aviation net carbon emissions by 50% in 2050, compared to 2005 levels [2]. Further improvement of known, existing technologies, operations and infrastructure are likely not sufficient to reach this long-term goal.

A European Union (EU) founded project designated as “Research on a Cruiser Enabled Air Traffic Environment” (RECREATE) is conducted to research on the feasibility of cruiser-feeder operations, i.e. cruiser aircraft that circumnavigate the earth and feeder aircraft that dock to the cruiser to exchange supplies and passengers. One possible concept of cruiser-feeder operations is aerial refueling. To substantiate the feasibility of aerial refueling for civil aviation associated with its significantly more stringent requirements on safety and availability as compared to military aviation, high fidelity models and simulations are necessary. Today there are two principal aerial refueling technologies: Probe-and-drogue refueling where the receiver aircraft has to actively control a probe into an uncontrolled basket and the flying boom method, where a boom that is attached to a tanker is controlled towards a receptacle on the receiver aircraft. For civil applications with large and unagile receiver aircraft, only the second method is viable.

This paper will especially address the modeling of an aerial refueling boom, its interaction with a receptacle, the influence of tanker aircraft movements on boom dynamics and vice versa.

For implementation of the model the SimMechanics toolbox as part of MATLAB/SIMULINK is utilized. SimMechanics is a multibody simulation environment for 3D mechanical systems. Using the afore-mentioned toolbox provides high flexibility with respect to design changes and insight into the boom system dynamics during concept phase that cannot be achieved by pure mathematical equations. SimMechanics supports automatic C-code generation which preserve the versatility of the simulation model. Anyway most statements made in this paper are also applicable to other modeling tools.

2. REFUELING BOOM DESIGN AND MODEL

2.1. Refueling Boom Design

In general an aerial refueling boom is a rigid pipe that is attached at its root end to the tail of a tanker aircraft by a pivot joint. This joint has two rotational degrees of freedom that allows pitching and yawing movements. Both possible rotary sequences are common. The boom considered in this paper first rotates about the vertical axis of the tanker z_{B1}, followed by a rotation about the lateral axis of the boom y_{BB} (see FIG. 1).

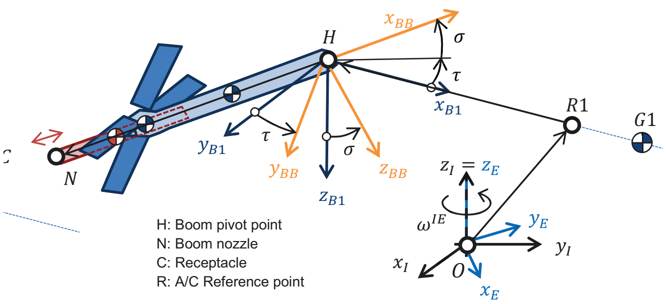

FIG. 1. Frames and rotation sequence

The rotation motion of the boom is controlled by aerodynamic control surfaces also referred to as ruddevators that are attached to the open end of the boom. Military boom designs are known two have only two ruddevators. For the reason of safety and availability for civil applications a third control surface is required that ensures that the boom maintains controllable in case of a single ruddevator failure. Since three control surfaces would require a symmetrical arrangement that would either cause problems with stowing the boom (when one ruddevator points up) or at take-off and landing (when one ruddevator points down) a symmetrical ruddevator configuration with four control surfaces has been chosen. The lower surfaces have a slight anhedral of -10 deg to minimize the impact on minimum lift-off speed and thus take-off run of the tanker, the upper surfaces have a dihedral of 30 deg.

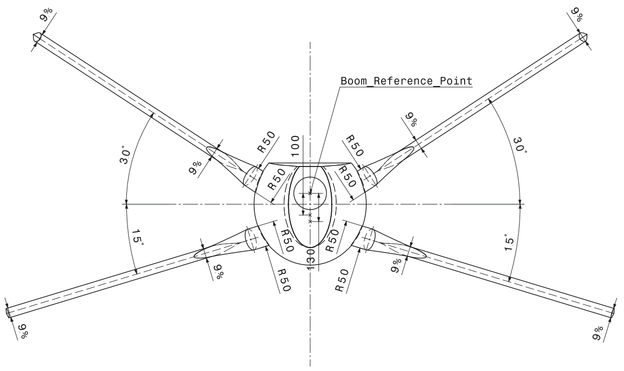

FIG. 2. Ruddevator arrangement [3]

A second rigid pipe is mounted within the first pipe that can be extracted to extend the range of the boom.

2.2. Refueling Boom Model

All components of the boom are modeled as rigid pipes and plates respectively. Weights and dimensions are based on the values of military refueling booms [4], but they are adjusted to account for the modified boom design leading to the rough mass breakdown given in TAB. 1.

Component	Mass	CG position from pivot joint
Pivot joint and connections	50kg	0m
Boom tube and fairings	260kg	5.5m
Ruddevator mountings and controls	100kg	10.5m
One ruddevator	30kg	10.5m
Extension pipe	170kg	5.7m + extension
Nozzle	30kg	11 + extension

TAB. 1. Mass breakdown [3]

Each ruddevator can be considered as separate body. Since the inertial influence of the individual rotations of the ruddevators on boom dynamics is very low, the ruddevators are condensed to their joint center of gravity and a joint non-diagonal inertia tensor.

The aerodynamic forces and moments of the ruddevators were calculated using panel methods. For the results presented herein the boom tube is assumed to have a spherical cross-section and its aerodynamic influence was approximated with handbook methods.

Instead of manually deriving the coupled tanker/boom equations of motion which was done in [4], the multibody simulation tool SimMechanics is used. Since SimMechanics is embedded in the Simulink environment, this enables an easy coupling between the boom model implemented in SimMechanics and an already existing tanker aircraft simulation model which is modeled in Simulink. In SimMechanics, several bodies specified by their mass, center of gravity (CG) position and inertia tensor can be linked at arbitrary positions by joints with definable rotational and/or translational degrees of freedom. Forces and moments can be applied to any body as well as states of each body and forces and moments acting on each hinge can be measured.

The boom simulation model is made up of six main bodies: The boom pivot joint, the boom tube, the ruddevators and their mounting and control, the extension pipe and the nozzle, shown in FIG. 3. The masses and CG positions are taken from TAB. 1, the inertia tensors are approximated by homogenous pipes and plates respectively. The bodies for the ruddevators, their mountings and controls are connected rigidly with the boom tube as well as the nozzle with the extension body. A prismatic joint connects the extension with the boom tube. During extension, the weight of the boom increases due to additional fuel flowing into the boom. To account for this effect, a virtual fuel body with variable mass is used. The aerodynamic forces and moments acting on the ruddevators and boom tubes are applied to the according reference points. The boom is attached to a virtual tanker body by a rotational joint with the previously mentioned rotation order. The virtual tanker body is driven by the translational and rotational states and state derivatives of the high-fidelity aircraft Simulink model. This coupling implicitly ensures that the constraint equation of the pivot joint is fulfilled, i.e. that the six independent degrees of freedom are reduced to two rotational degrees. To close the loop the reaction forces and moments on the boom pivot point are measured and feed back to the equations of motion (EoM) of the tanker aircraft as additional external forces and moments (see FIG. 3).

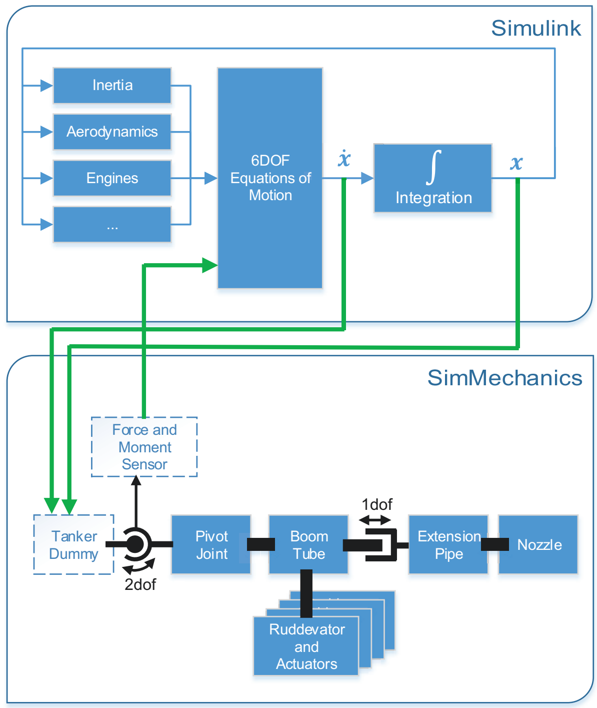

FIG. 3. Coupling of the simulation models

Since the state derivatives of the tanker are used as inputs to the boom simulation model and the forces and moments acting on the boom hinge - which are used to close the loop – are themselves dependent on the state derivatives of the boom and thus also on the state derivatives of the tanker aircraft, an algebraic loop occurs, i.e. the inputs of a function are dependent of the outputs of the same function at the same time. Simulink provides specific algebraic loop solvers which however slowdown simulation significantly since this mathematical problem can only be solved iteratively. This problem is solved by delaying the feedback from the boom to the tanker by a single time step which is legitimate since this coupling is very small (see chap. 2.3).

The SimMechanics model as described above presupposes a flat, non-rotating earth, i.e. eq. 1 is solved:

$$(1) \qquad \left(\vec{a}_K^{G,i}\right)^{EO} = \frac{1}{m_i} \cdot \sum \vec{F}_{Ext,i}$$

$\vec{a}_K^{G,i}$ denotes the kinematic acceleration of the center of gravity G of the i-th body, the superscript EO denotes that the velocity with respect to the earth centered earth fixed frame E is differentiated with respect to the earth-parallel North-East-Down frame O. m_i is the mass of the i-th body and $\vec{F}_{Ext,i}$ are the external forces that act on the i-th body. To be numerically correct, the boom simulation model must comply Eq. 2:

$$(2) \qquad \left(\vec{a}_K^{G,i}\right)^{II} = \frac{1}{m_i} \cdot \sum \vec{F}_{Ext,i}$$

The equation specified in (1) is extended to have the same Euclidean reference frame as the aircraft model, i.e. an earth-centered inertial frame I:

$$(3) \qquad \left(\vec{a}_K^{G,i}\right)^{EO} = \frac{1}{m} \cdot \left(\sum \vec{F}_{Ext,i} + \Delta\vec{F}_{Frame,i}\right)$$

Using the rules for time derivatives in moving frames, the acceleration with respect to the inertial frame $\left(\vec{a}_K^{G}\right)^{II}$ can be split up:

$$(4) \qquad \left(\vec{a}_K^{G,i}\right)^{II} = \left(\vec{a}_K^{G,i}\right)^{EO} + 2\vec{\omega}^{IE} \times \left(\vec{v}_K^{G,i}\right)^{E} + \vec{\omega}^{IE} \times \left(\vec{\omega}^{IE} \times \vec{r}^{G,i}\right) + \vec{\omega}^{EO} \times \left(\vec{\omega}^{EO} \times \vec{r}^{G,i}\right)$$

$\vec{\omega}^{IE}$ denotes the (constant) earth rotation rate, $\vec{\omega}^{EO}$ the rotation of the NED-frame with respect to the E frame which is referred to as transport rate. Combining eq. (2)-(4), the compensation forces that are applied to each body of the boom simulation model are obtained.

$$(5) \qquad \Delta\vec{F}_{Frame,i} = m_i \cdot \left(-2\vec{\omega}^{IE} \times \left(\vec{v}_K^{G,i}\right)^{E} + -\vec{\omega}^{IE} \times \left(\vec{\omega}^{IE} \times \vec{r}^{G,i}\right) - \vec{\omega}^{EO} \times \left(\vec{\omega}^{EO} \times \vec{r}^{G,i}\right)\right)$$

Substituting a velocity of 230 m/s and a flight altitude of 10km in eq. (5) gives an upper bound of 48.3N for the centrifugal force and 21.4N for the Coriolis force (based on the total boom weight), which correlates with 0.7% of the total boom weight.

2.3. Boom Simulation Results

Since the boom model defined herein is an all new design no direclty comparable simulation results are available for a boom with four control surfaces and of this size. To verify the principle correctness of the simulation model, the results are compared to available simulation results of military aerial refueling boom configurations [4]. As test case a symmetrical ruddevator deflection of 6 deg about the trim condition is used at an airspeed of 230m/s and an altitude of 26000ft (FIG. 4).

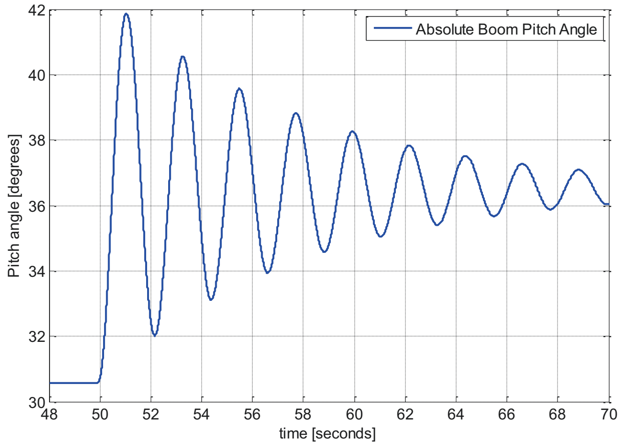

FIG. 4. Boom pitch response to symmetrical 6 deg ruddevator deflections

Comparing the result from FIG. 4 with the one given in [4], it can be seen that the control authority is approximately the same for both configurations, i.e. the steady state reaction on a symmetrical six degrees ruddevator deflection is almost the same for both designs. This can be explained by the reduced ruddevator size of the new boom configuration and the increased weight due to additional ruddevators and actuators. Frequency and damping of the response are lower for the new configuration which can also be explained by the higher weight and moment of inertia.

To evaluate the reaction of the boom on pivot point excitations and hence tanker motions, a test case with a sinusoidal tanker pitch excitation is defined. Figure 5 shows the excitation and the reaction of the boom about the trim. The absolute pitch angle with respect to the earth surface is displayed instead of the pitch angle of the boom pivot (i.e. σ in FIG. 1) to avoid direct correlation between the displayed excitation and the response. It can be seen that the reaction of the boom motion on pivot point excitations is significant and thus cannot be neglected.

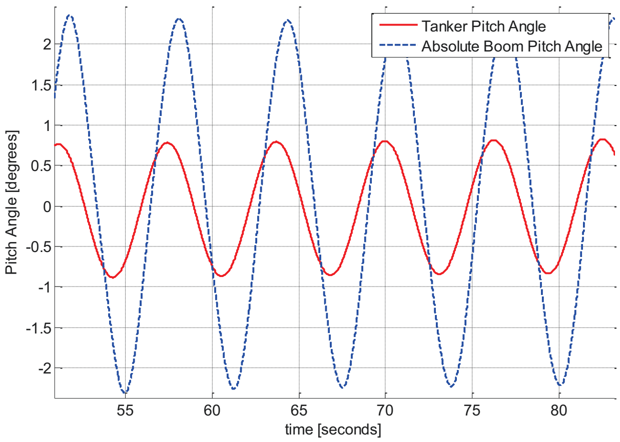

FIG. 5. Boom pitch response to sinusoidal tanker pitch excitation

The reaction of the tanker on boom movements is evaluated in another test case with a sinusoidal boom pitch angle excitation of 10.5 degrees about trim. For the tanker a simulation model of a large four-engined transport aircraft is used. Figure 5 depicts the oscillation of the boom pitch angle about the trim and the difference between tanker pitch angle with and without coupling. The tanker pitch angle difference is scaled by a factor of 1000, i.e. considering the feedback from the boom to the tanker leads to an average increase of the tanker pitch angle of 0.003deg due to boom weight, and oscillations of 0.0005deg due to boom pitch oscillations. Hence this coupling can be neglected without loss of generality.

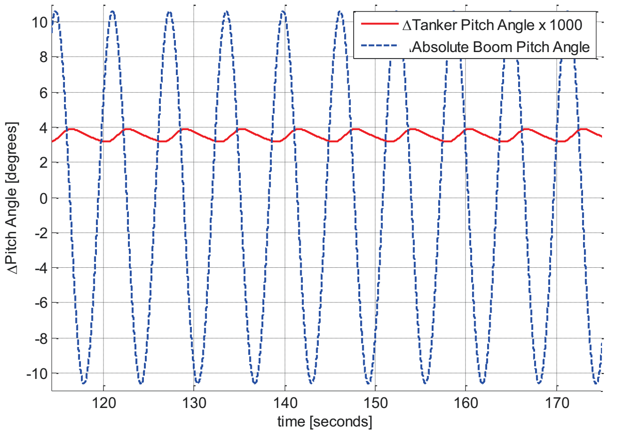

FIG. 6. Tanker pitch response to sinusoidal boom pitch excitation

3. RECEPTACLE DESIGN AND MODEL

The receptacle installation is the counterpart of the boom nozzle mounted on the fuselage of the receiver aircraft. To support the connection process, the receptacle installation also comprise some sort of guidance towards the receptacle. For military aerial refueling the Universal Aerial Refueling Receptacle Slipway Installation (UARRSI) has been found to be the best compromise for a receptacle installation in relation to performance, function, volume required, weight, maintenance and cost [5]. The UARRSI consists of a slipway that guides the nozzle of the boom to the receptacle and the receptacle itself, shown in FIG. 7.

FIG. 7. UARRSI with aerial refueling boom[1]

3.1. Receptacle Model

For the receptacle model described in this paper a similar design is chosen, see FIG. 8.

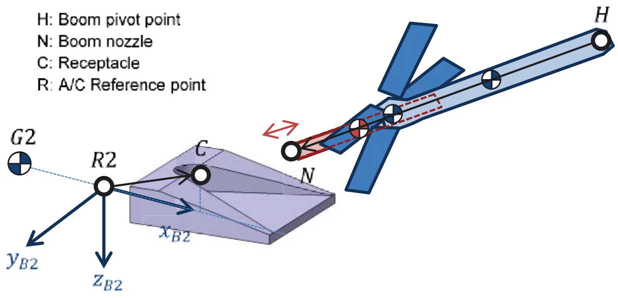

FIG. 8. Tanker frame and receptacle nomenclature

To model the slipway, the receptacle is split up into four main contact surfaces: The actual slipway, the left and right limitation walls and the upper surface of the receptacle. Subsequent the determination of the reaction force of the left wall is described. The reactions of all other surfaces can be obtained analogously to this case. Figure 9 shows the top view of the receptacle installation.

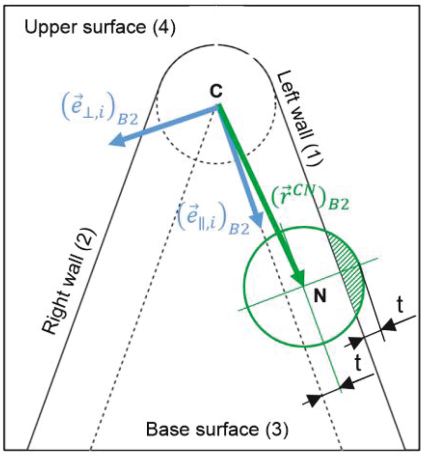

FIG. 9. Receptacle installation top-view

C denotes the receptacle center, N the boom nozzle center and t the penetration depth of the boom nozzle into the wall. $(e_{\parallel,i})_{B2}$ and $(e_{\perp,i})_{B2}$ are the unit vectors in direction of the i-th surface and perpendicular to it respectively. Figure 10 gives the flow chart for the determination of the reaction force. First it is checked if the surface is intruded. The upper equation is to determine if the surface plane is intruded. The lower determines if the intrusion is within the vertical extend of the surface. If any of the two inequality constraints is not fulfilled the boom nozzle does not tangent the surface and thus no reaction force acts. If both are fulfilled, the penetration depth and magnitude of the reaction force is calculated. The direction of the reaction force is perpendicular to the surface. This sequence is carried out for each surface and during each time step.

The reaction force is a function of the penetration depth. For a continuous system, it can be calculated from material and geometric properties of the boom nozzle and the receptacle. This relation is in general nonlinear. Since the

[1]http://www.lockheedmartin.com/us/news/press-releases/2011/march/HC-130JCompletesDevelopme.html [cited 20 August 2013]

intrusions are small, eq. 6 is used for approximation with the stiffness parameter k.

(6) $$\left(\vec{F}_{Reaction,i}\right) = k \cdot t_i$$

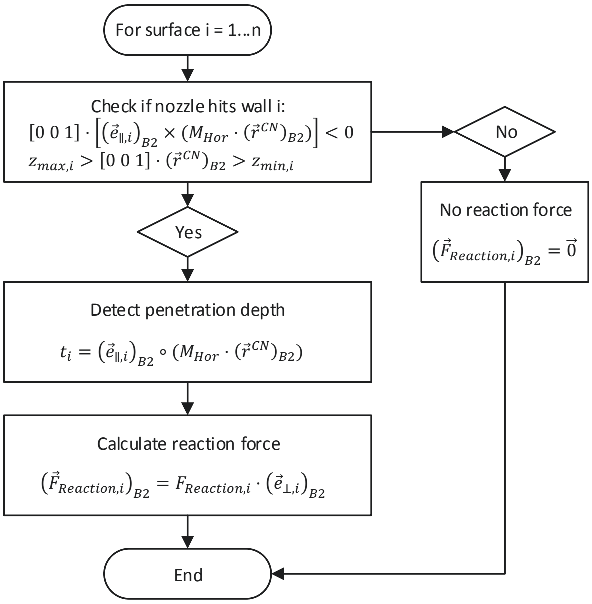

FIG. 10. Flow chart for calculation of the reaction force

For discrete simulations with limited simulation frequencies, such holonomic[2] constraints cause numerical stiffness in the system, i.e. the solution of the equations of motion of the boom can become numerically unstable if the variation of the solution is too fast. High stiffness coefficients cause high accelerations that are integrated for the duration of a time step which can be significantly longer than the duration of an (elastic) impact. Knowing the inertia properties of the boom, the discrete sample time and the maximum expected contact velocity, a critical stiffness coefficient can be calculated so as the boom nozzle is forced to be out of the intruded body within one time step. However, this would cause the reaction velocity to be higher than the impact velocity which is not reasonable (super-elastic collision). To encounter this undesired behavior the stiffness coefficient is chosen lower than the critical stiffness and an additional damping term is introduced that limits the absolute value of the velocity after the impact to the value of the velocity before the impact. This simplification is acceptable since for normal operation the contact velocity is low.

(7) $$\left(\vec{F}_{Reaction,i}\right) = k \cdot t_i + d \cdot \dot{t}_i$$

The reaction forces of all surfaces are superposed and applied as external force onto the boom nozzle.

3.2. Receptacle Simulation Results

As test case the normal military boom connection maneuver is applied. For that, the boom is not controlled directly to the receptacle but the boom nozzle is brought into contact with the slipway using a higher boom pitch angle. By extending the extension of the boom, the nozzle automatically slips towards and into the receptacle. Figure 11 displays the resulting boom pitch and nozzle force. In the first phase, the boom is controlled to a pitch angle of 31 deg followed by a gradual extension of the boom (I). As soon as the nozzle hits the slipway an upward force occurs. With further increasing extension the nozzle slips towards the receptacle forcing the boom pitch angle to decrease (II). As soon as the boom nozzle reaches the receptacle, they are coupled using a conventional mass-spring-damper system to ensure that the nozzle follows the receptacle movements.

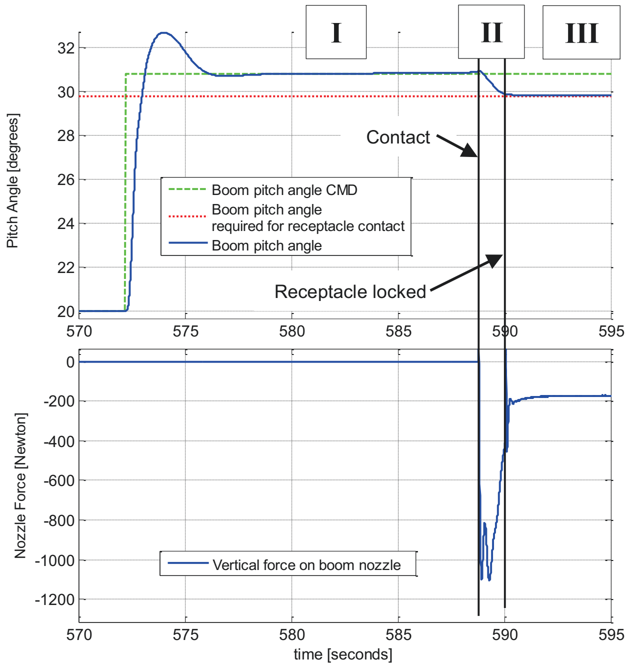

FIG. 11. Receptacle simulation results

4. CONCLUSIONS AND PERSPECTIVES

Methods have been described for modeling of a novel boom design. The coupling with the tanker aircraft dynamics and the interaction of the boom and the receptacle have been discussed. SimMechanics has been used for boom simulation and the boom model has been linked to a high-fidelity aircraft simulation model in Simulink. Using SimMechanics has proven high usefulness and flexibility during concept and design phase. This tool also easily enables measurement of forces and moments which are useful for boom design and construction. Such measurements can also be used for simulation of boom overload and forced disconnect scenarios. So far, some tests have been conducted with the model showing its physical correctness and high fidelity. It has also been proven that the model implemented in SimMechanics can be successfully autocoded and operated under real-time conditions.

The model can be improved by more accurate aerodynamic data from FEM-simulations and wind tunnel experiments, and more detailed inertia properties, e.g. using CAD tools. Furthermore, comparison with other modeling techniques would increase confidence in model correctness.

5. ACKNOWLEDGMENTS

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[2] Restriction of position states

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