**Nationaal Lucht- en Ruimtevaartlaboratorium**
National Aerospace Laboratory NLR

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# ACCELERATION MEASUREMENTS ON SLOSHSAT FLEVO FOR LIQUID FORCE AND LOCATION DETERMINATION

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## ABSTRACT

Sloshsat FLEVO is a spacecraft for the experimental study of liquid dynamics and liquid management problems in space. It is to be launched from a Hitchhiker bridge on the Shuttle, and operated via the Shuttle in its vicinity. Of the total 120 kg mass of Sloshsat, 33.5 kg is liquid water in a smooth 87 liter tank. The operation of Sloshsat is controlled with an orthogonal set of 12 nitrogen gas thrusters of 0.85 N each. The response of Sloshsat to the control thrusts is predicted from the Sloshsat Motion Simulator. SMS has a newly-developed model for the liquid, the ‘slug’. It is represented by a nonlinear ordinary differential equation for a ‘soft’ spring. The differential equation describes the behaviour of a homogeneous sphere of constant mass but variable radius, with surface tension. The internal energy resides in radial oscillation, angular momentum and surface potential. The slug provides a point of contact with the tank and the location of its center of mass. At these points linear and angular velocities are calculated and are used to specify the interaction with the tank. Sloshsat FLEVO is instrumented with six linear accelerometers and three gyroscopes. The data from these sensors give the motion of the tank. Since the inertial properties of the empty Sloshsat are known, the force and torque on the tank can be calculated. For known thrust the liquid force and torque result. The slug model can be inverted to give the sequence of center of mass locations from a sequence of force and torque data, if the magnitudes are sufficiently large. From these data can be calculated the slug force and the spacecraft accelerations that would be experienced if there were no thruster activation.

## INTRODUCTION

The liquid in a tank on a navigating vehicle will slosh about and exert reaction forces on its enclosure. If the liquid and the solid masses are comparable in magnitude, the dynamics of the system are strongly coupled. For a spacecraft, excursions in all three spatial dimensions may need to be considered, in addition to rotational motion.

The practical problem is phrased as: how can forces and/or torques of limited magnitude be applied to a vehicle with liquid in order to steer a desired course? A corollary to this question is the identification of free motions, i.e. without application of steering input, from (selected) initial conditions; yet another is the design of desirable courses (manoeuvres).

Much of the early work in slosh dynamics (N.N. 1972, Guibert 1978) was related to liquid fueled rockets and their stability. This is still a relevant subject, as exemplified by the much-studied PAM-D instability. The Perigee Assist Module has a solid rocket motor, and so, when a coning instability was observed during launches of STAR 48 comsats, the comsat liquid stores were suspected. Simulations, with a spherical pendulum model, showed that this liquid was not responsible for the observed instability (Hill et al. 1988). Eventually the cause of the instability was traced to a small liquid residual of the solid fuel, that collects in the motor casing (Or 1992; Yam et al. 1997). Simulation of the dynamics, using a modification of SMS with a variable mass slug (Vreeburg 1997), showed the behaviour to be consistent with a secular instability of the system (Lamb 1907).

On 20 Dec. 1998 the NEAR spacecraft, after a 200” settling burn, activated its main (bi-propellant) engine for orbit insertion about asteroid Eros. Within one second the onboard control system terminated the burn, because the lateral acceleration exceeded its allowed limit value (Dunham 1999). The cause of the anomaly was a wrong prediction of the liquid fuel reaction on the spacecraft, which illustrates the need for better modeling.

The requirements for reliable theory of liquid-tank interaction become even more urgent with the operation of the International Space Station; traffic about the station will include many spacecraft that contain liquid.

## SLOSHSAT FLEVO

A small spacecraft dedicated to investigation of liquid dynamics in spacecraft is now being prepared (Vreeburg and Soo 1998). It is Sloshsat FLEVO, to be launched from a Hitchhiker bridge in the Shuttle payload bay, with a program of experiments on liquid transfer, slosh modes and spacecraft dynamics. The rigid part of the spacecraft is instrumented with accelerometers and gyroscopes, and so acts as a dynamometer whose motional data are to be processed to get the values of the force and torque that the liquid exerts on the tank. Comparison of measured sequences with predictions by CFD, and other methods, is intended for the validation of models.

A sketch of Sloshsat FLEVO is given as figure 1.

The spacecraft is box-like with dimensions 0.78 x 0.74 x 0.56 m$^3$ and has a dry mass of 93 kg. Fluid stores are 1.6 kg of nitrogen gas, for the 12 thrusters of the

Reaction Control System, and 33.5 kg water in a 87 liter tank. The tank shape is a straight cylinder of length equal to cross-section radius, capped by hemispherical ends. Except for minor intrusions by sensors, the tank has a smooth interior wall, made from polyethylene. The Motion Sensing Subsystem (Dujardin 1997) is composed of six linear accelerometers (Allied Signal QA-3000-010) and three gyroscopes (LITEF μ -FORS). The accelerometers are installed in three orthogonal pairs at three corners of the box. The six accelerometer output are corrected for centrifugal acceleration, from the gyro measurements, and are then solved for linear and rotational acceleration components.

Control of Sloshsat motion is required in order to control the liquid in its tank. The preparation and verification of control strategies must be done with a simple model of the system that forms the basis of a numerical simulator. When a control strategy has been determined with this model, a simulation run with a CFD model of the liquid may obtain final verification. The simple model for Sloshsat is included in SMS, the Sloshsat Motion Simulator. It is a mass-spring-damper model with some unusual features, constructed about two key points in the system: the liquid pressure point and the liquid center of mass. More details are given below.

## RECONSTRUCTION OF LIQUID FORCE AND MASS LOCATION

### *SMS slug model*

The experiments with Sloshsat are designed to keep liquid coherent. Nominally, the water will move as a single body in the tank. Sequences of force and torque values on the tank allow to identify a pressure point trajectory on the tank wall. In the pressure point the exchange of linear and angular momentum between liquid and tank is taken to occur. The liquid mass is denoted ‘slug’ in SMS; its properties are explained next. SMS is unique for its use of a variable separation between slug c.o.m. and pressure point. This distance, symbol y, is used as characteristic size of the liquid distribution and so enters geometric variables in dynamic quantities, like wetted area to calculate friction, or moment of inertia for the calculation of liquid rotation rate from its angular momentum. The angular coordinates, about the tank center, of the slug c.o.m. in SMS are equal to those of the pressure point. It is a nonessential simplification that can be removed if need be. Another is that both the tank and the slug mass have a spherical configuration. Figure 2 shows a spherical mass in contact with a solid wall at the pressure point, subject to body force B. Require the mass density to be uniform over the sphere and calculate the spherical collapse. Then, from conservation of mass, the velocity field in the sphere is radial, with a magnitude linearly related to radial location. Contact with the wall makes the center velocity component along the normal equal to the slug radial velocity at the pressure point.

The (internal) energy of a spherical slug of mass m and size y is composed of:

capillary potential energy $P_c = 4\pi\sigma y^2$ (from surface tension σ)

kinetic energy in collapse (or expansion):

$$T_d = \frac{3}{10} m\dot{y}^2$$

kinetic energy in angular momentum $\underline{H}$ :

$$T_H = \frac{5}{4}\frac{H^2}{my^2}\left( = \frac{1}{2}\underline{\Omega}\cdot\underline{H} \right)$$

For a lossless slug the work by force -N on the slug is converted to energy: -N dy = d ($P_c$+$T_d$+$T_H$)

$$\text{or: } \frac{3}{5} m\ddot{y} + 8\pi\sigma y - \frac{5}{2}\frac{H^2}{my^3} + N = 0 \qquad (1)$$

the constitutive equation for the slug dynamics. The slug model predictions have been compared with predictions of liquid c.o.m. motion and liquid reaction force as calculated by a CFD method, and, for the analyzed example, were found to agree well (Vreeburg 1999).

### *Dynamic equations and analysis:*

The equation of linear motion for the tank is:

$$\frac{d\underline{V}}{dt} + \dot{\underline{\Omega}} \times \underline{r}_Z + \underline{\Omega} \times (\underline{\Omega} \times \underline{r}_Z) = \frac{N}{M_T}\underline{e} + \frac{\underline{F}_E}{M_T} \qquad (2)$$

The angular momentum is conserved by (neglect liquid friction torque)

$$\underline{\underline{I}} \cdot \dot{\underline{\Omega}} + \underline{\Omega} \times \underline{\underline{I}} \cdot \underline{\Omega} = \underline{T}_E - \underline{r}_Z \times \left( \underline{F}_E + N\underline{e} \right) \qquad (3)$$

The linear motion for the slug c.o.m.:

$$m\left[ \frac{d\underline{V}}{dt} + \dot{\underline{v}} + 2\underline{\Omega} \times \underline{v} + \dot{\underline{\Omega}} \times \underline{r} + \underline{\Omega} \times \left( \underline{\Omega} \times \underline{r} \right) \right] = -N\underline{e}$$

multiplication by $\underline{e}$ results in:

$$\ddot{r} + \underline{e} \cdot \frac{d\underline{V}}{dt} + \frac{N}{m} = r\left[ \underline{e} \times \left( \underline{\Omega} + \underline{w} \right) \right]^2$$

where m, $M_T$ = slug, tank mass
$\underline{r}$ , $\underline{r}_z$ = slug, tank c.o.m. location
$\underline{\underline{I}}$ = principal inertia tensor of tank
$\frac{d\underline{V}}{dt}$ = tank linear acceleration
$\underline{\Omega}$ , $\dot{\underline{\Omega}}$ = tank rotation rate, acceleration
$\underline{F}_E$ , $\underline{T}_E$ = thruster force, torque
$\underline{e}N$ = liquid normal force $\underline{N}$

The quantities relevant in the tank coordinate system are (a superscript dot means time derivative):

$R =$ tank radius
$\underline{r} = r\underline{e} =$ slug center location
$\underline{v} = \dot{\underline{r}} = \dot{r}\underline{e} + r\underline{w} \times \underline{e} =$ slug center velocity
$\underline{w} = \underline{e} \times \dot{\underline{e}} = \frac{1}{r}\underline{e} \times \underline{v} =$ swirl
$\underline{\omega} =$ slug relative rotation rate

Considering that $\ddot{y}$ from equation (1) is $-\ddot{r}$ from equation (4) and $H^2 = \left[\frac{2}{5}m(R-r)^2(\underline{\Omega} + \underline{\omega})\right]^2$ allows to eliminate the slug (relative) acceleration from equation (4), to yield equation (5):

$$N = m\left[\frac{3}{8}\left\{r[\underline{e} \times (\underline{\Omega} + \underline{w})]^2 - \underline{e} \cdot \frac{d\underline{V}}{dt}\right\} + \frac{1}{4}(R-r)(\underline{\Omega} + \underline{\omega})^2\right] - 5\pi\sigma(R-r)$$

Equation (5) is the basic one for the present subject. It is used in SMS for the recovery of r, and then for the calculation of the linear and angular accelerations that the tank would have if the thruster force and torque were zero. And, the slug reaction force at no thruster activation. It is noted that equation (4) holds also for liquid in such a tank as has $\underline{r}$. $\underline{N}$ = r N.

The term that contains the slug inertial rate of rotation in equation (5) corresponds to the liquid angular momentum and is not measurable in practice. It has been neglected in the analyses. The consequence, as determined from the present simulation, is small and influential only on the magnitude of the maximum tension force that can occur between the slug and the tank wall. This magnitude is relevant to the declaration of the slug state: 'frozen' i.e. at its minimum size, or 'breathing'. The state declaration helps to select between positive and negative values of the normal force direction, and so between the sectors of the tank where the slug is located. Rather than neglect, one may assume a value for the slug inertial rotation rate if relevant information can be had.

The motion sensing subsystem of Sloshsat supplies all terms on the left hand side of equation (2), whence knowledge of the thrust allows to determine the value of the liquid force vector under thrust. With small error this vector is equal to the normal force (special cases excepted), and so gives the direction and magnitude, provided it is large enough to be trusted. The direction $\underline{e}$ with its previous values is used to generate the value for the swirl, which leaves everything in equation (5) known except for distance r that thereby is solved. In equation (3) the liquid friction torque has been neglected, a simplification that could be verified also from the measurement data.

Substitution of equation (5) in equations (2) and (3) allows to aggregate the tank acceleration terms in these equations. Then , putting the thrust terms to zero and substituting the known values of $\underline{\Omega}$, $\underline{e}$ and r, some algebra yields the values of linear and angular accelerations that the tank would have had in absence of thruster activation. Substitution of the calculated linear acceleration in (5) gives the zero-thrust slug reaction force.

An option to be evaluated is to derive the angular acceleration from the exact solution for the rigid body under no forces, using the measured angular rate, and process this information for the prediction of thruster performance.

*Example*

The equations from the preceding section have been included in SMS, and tested during a simulation of a somewhat arbitrary manoeuvre of Sloshsat. SMS has provisions to set the delays between data collection and processing, contaminate exact measurements with noise and deselect data that are not reliable, e.g. due to thruster valve action impacts. The accelerometer noise has been set at $10^{-4}$ m/s$^2$, multiplied by an arbitrary number between –0.5 and +0.5. The initial condition has Sloshsat at rest for 3" with the slug near the extreme –X location in the tank. Settling thrust is applied for 8" along the +X direction. Then, after a 2 " period of no thrust, thrust is applied along the –X direction for 30". All commanded thrusting is continuous and has magnitude 1.7 Newton. Autonomous control generates torques that try to null Sloshsat rotation rate, and it is found that this rate is oscillatory with an amplitude of about 0.02 rad/s. The motion is followed for 200", and some relevant results are shown in figures 3 to 5.

The qualitative behaviour of the slug is that of a ball that rolls and slips over the wall of the tank. Thus, the slug builds up rotation rate during its translation. After about 150" its linear velocity is damped to insignificance, but its angular rate has built-up to about 0.25 rad/s. Since the contact area between the slug and the wall is relatively small (the slug is at minimum size) there is not much friction and the slug spin will take some time to die out. The slug is kept coherent by surface tension and shows capillary oscillation. Quantitative predictions are discussed from the figures. Figure 3 shows the magnitude of the normal force. If the resulting acceleration on the tank gets below $10^{-4}$ m/s$^2$ the algorithm in SMS puts it to zero and stops processing. The essential data like reaction force direction are then progressed by extrapolation. From about 100" on, the force is near zero, and this is reflected in figures 4 and 5 that show predictions derived from the measured normal force vector. For the near zero values no useful predictions are made, but it is found that good values are obtained again when the force magnitude has grown sufficiently large. The direction of the normal force, which is also to the slug center, is reconstituted closely when the force magnitude is large enough. In figure 5 the X-component is plotted only, but the other components show similar behaviour. If the direction is not well predicted, neither can be the swirl since it is the rotation rate of the direction. Thus, reconstitution of the distance from slug to tank center, which needs the swirl, becomes seriously degraded, as shown in figure 4. In figure 3 the bad swirl values cause a wrong prediction of the normal force magnitude between 120-150". For comparison, predictions made with the actual swirl values have been plotted also.

## CONCLUSION

A simple model for the prediction of the liquid reaction force has important uses for spacecraft control, but of course only if it has been validated. The slug model in SMS is being evaluated for this purpose, in anticipation of flight data from Sloshsat FLEVO. The analyzed example indicates that also with limited knowledge, e.g. of the angular momentum of the slug, relevant predictions can be made, even if only under favourable conditions. Hence, liquid models with the right structure may require just a few parameters and thus can be simple.

## ACKNOWLEDGEMENT

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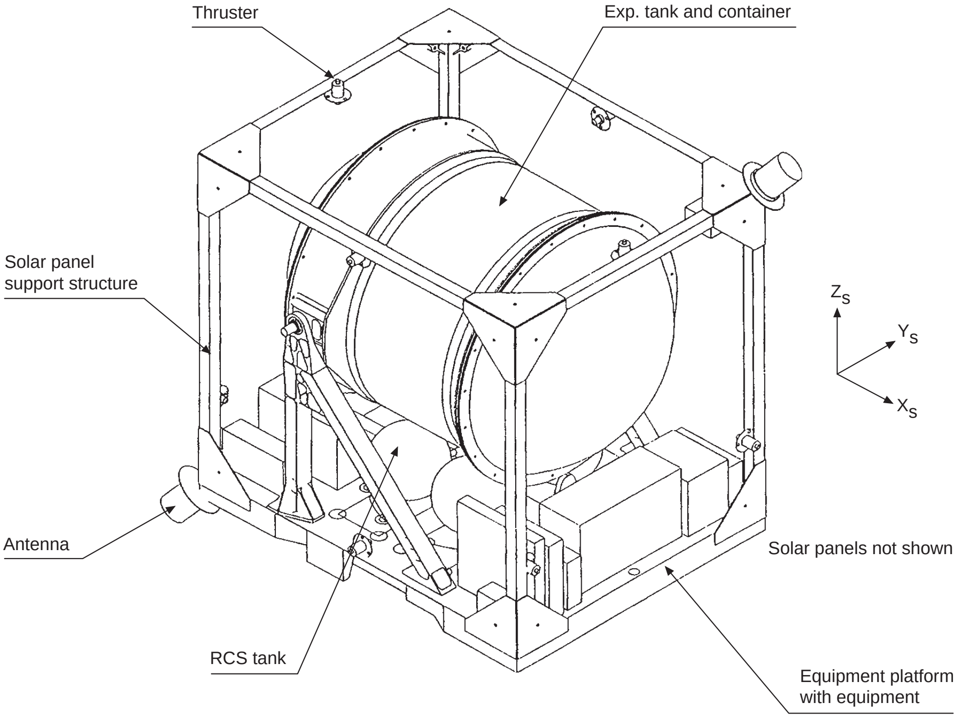

*Fig. 1 Sketch of Sloshsat FLEVO*

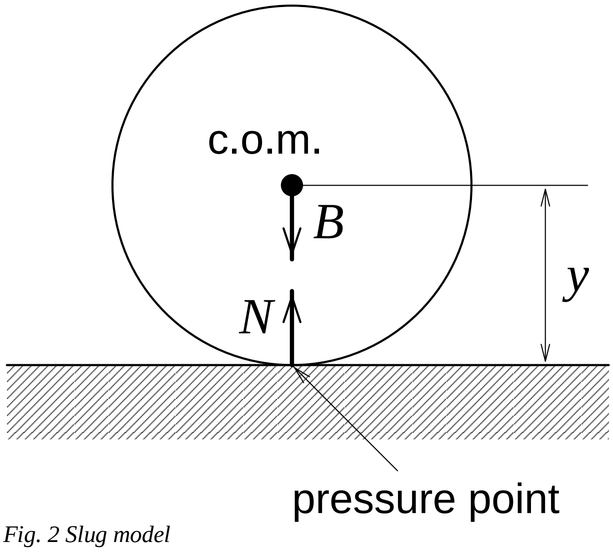

*Fig. 2 Slug model*

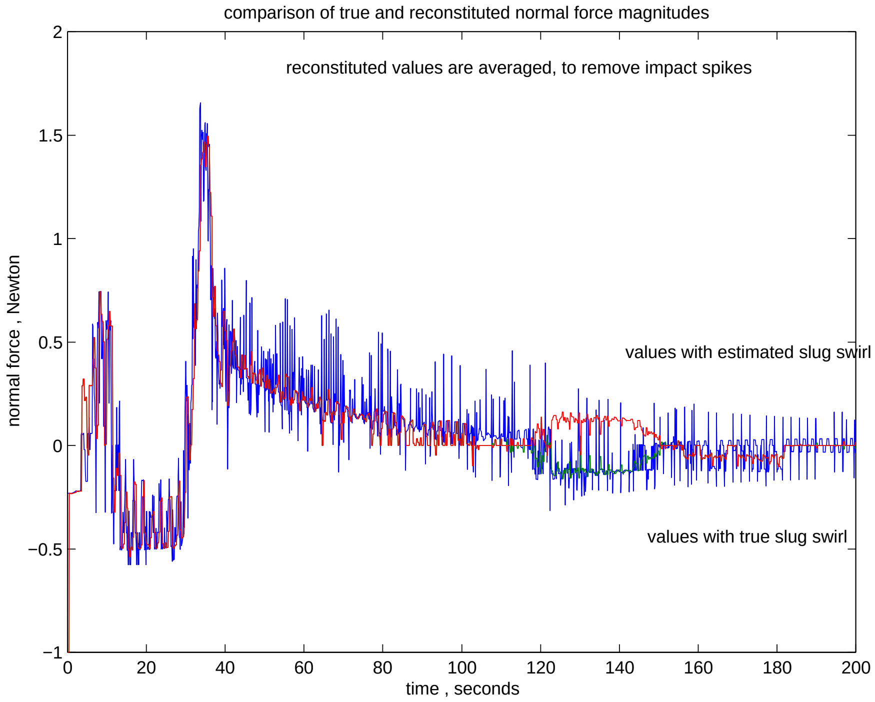

*Fig. 3 Calculated true normal force and its value reconstituted from simulated measurements*

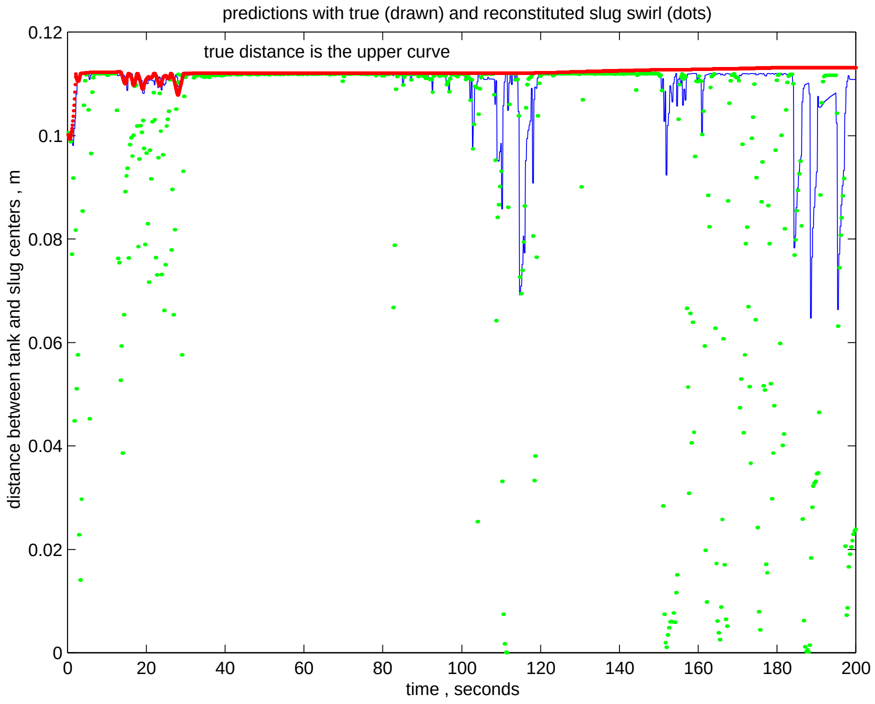

*Fig.4 Predictions of slug center distance from the center of the tank*

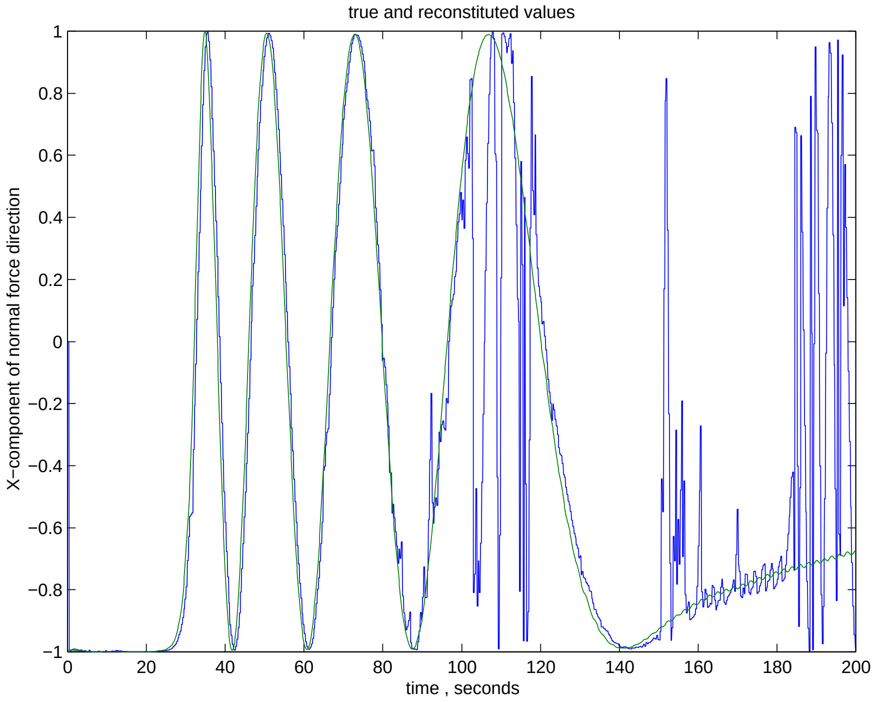

*Fig. 5 X-component of the direction of the normal force, true and predicted from measurement data*