Comfort Evaluation Criteria for Pitching Vibration Damping of Agricultural Tractors

Dr. Thomas H. Langer, MSc Kaspar Holm-Petersen, Danfoss Power Solutions, Nordborg, Denmark
Dipl.-Ing. Dirk Metker, CLAAS Selbstfahrende Erntemaschinen GmbH, Harsewinkel, Germany

Abstract
The market of agricultural machinery continuously increases its demands for better comfort and higher safety for the end user. This poses a challenge for OEM’s in order to develop new suspension and damping techniques and, indeed, how to quantify good ride comfort. The standardized method to evaluate comfort is utilizing ISO 2631-1, but due to the frequency weighting filters include in this standard, it does not capture the effect of pitching vibration damping.

In this paper, a comfort evaluation criterion for pitching vibration damping of agricultural tractors is presented. The aim is to quantify ride comfort when developing solutions for damping of pitching vibrations in order to compare different strategies.

The developed criteria shows good correlation with the subjective comments from a number of test drivers.

Introduction
The business segment of agricultural tractors represents a highly competitive field, where almost all manufacturers due to customer demand of low fuel consumption and strengthened emission standards perform quite equally concerning efficiency. Then two factors are left in the competitive game; intelligent features and good operator comfort. One of the cornerstones of operator comfort is the tractors vibration attenuation performance in order to reduce the vibration exposure on the operator.

Most agricultural tractors with inflatable tires are facing the problem of low frequency oscillations during transit operations. The first natural order of many tractors are pitching due to relative short wheelbase and high inertia. The pitching movement, Fig. 1, typically occur at a frequency of approximately 1Hz and the amplitudes can increase to an intensively levels if the oscillations
are not damped. Often, the operator has to decrease travel speed to reduce the oscillations\textsuperscript{[1]}. The pitching oscillations not only result in discomfort; the need of decreasing speed reduces productivity and the presence of the oscillation contribute to higher fatigue of the tractor chassis and a potential risk to loose directional control of the vehicle due to variation of road contact of the steering tires.

![Figure 1: Pitching movement of an agricultural tractor with front weight and plough.](image)

In general, two paths exist to reduce vibration exposure; 1) by introducing additional degrees of freedom in terms of dedicated suspension systems\textsuperscript{[2,3,4,5]} or; 2) damping of vehicle oscillations by engaging the existing actuators like the rear hitch of a tractor\textsuperscript{[6,7,8,9]}, which is simpler, reduce maintenance and is less costly than a dedicated suspension system. Independent of the technical solution, whether it is a dedicated suspension system or based on the tractor hitch, whether it is passive, semi-active or active, the crucial question is of course how well do the dampening work – or in other words; how much is the comfort improved.

ISO 2631-1 sets the standard on how to evaluate comfort in terms of whole-body vibration (WBV)\textsuperscript{[11]} and the method is also recognized by the European Directive EC/2002/44 that contains directions for work related vibration exposure and defines an action value and a limit value for the eight-hour daily exposure to WBV for the human operator\textsuperscript{[12]}. Utilizing EC/2002/44 and ISO 2631-1 for evaluation for oscillation damping of pitch movement poses some challenges; EC/2002/44 only consider translational accelerations evaluated in the seat. Hence, the resulting longitudinal acceleration resulting from the pitching movement will be highly dependent on seat position, cabin and seat suspension. Another challenge by applying ISO 2631-1 is the defined frequency weighting filter, which primarily pass acceleration in the range of 1-4Hz. Hence, for a vehicle with a low natural first order below 1Hz, the transients will not be captured. Low frequency oscillations below 1Hz is not damaging to the human body, but can cause motion sickness and therefore still comfort related. In order to quantify ride comfort when developing and benchmarking solutions for damping of pitching oscillations an evaluation method is needed.
Proposed Evaluation Criteria

The proposed evaluation method for pitch oscillation damping is based on the methodology of ISO 2631-1 by summarizing the pitch oscillations in terms of the root-mean-square acceleration after applying a 5Hz low pass filter:

$$\dot{\omega}_{RMS,y} = \left[ \frac{1}{T} \int_0^T (\dot{\omega}_{5Hz}^2(t)) dt \right]^{1/2}$$

The method is suitable for evaluation of a tractor that drives through a defined track with a given speed and recording the time signal for a well-defined period $T$.

This method has a number of advantages; as rotational acceleration is considered, the mounting of the accelerometer can be placed anywhere on the tractor chassis. Second, the evaluation method is similar to the one in ISO 2631-1 for which a good correlation with subjective ride comfort experience exists\cite{12,13,14}. Third, by only applying a low pass filter, the method is suitable for tractors with low first natural order pitching.

Experimental Setup

In order to demonstrate the usage of the proposed evaluation method, it has been applied for an implementation project of active hitch damping on an agricultural tractor. The tractor in concern is the CLAAS Xerion 5000, Fig. 2, and the electro-hydraulic hitch control system is delivered by Danfoss consisting of dedicated double acting hitch valves, PVBZ-HD, pressure sensors and a MC024 controller which is operated through the CLAAS Electronic on-Board Information System (CEBIS), Fig. 3. All communication is established through the CAN bus. For evaluation purpose a Honeywell 6DF-1N6-C2-HWL accelerometer that utilizes CAN communication is mounted to a rigid part of the chassis.

Figure 2: CLAAS Xerion 5000 with test plough rear and front weight.
Figure 3: Hitch control system implemented on CLAAS Xerion 5000. Further details can be found in [15].

The 100m smooth version of ISO 5008\textsuperscript{[16]} serves as boundary condition, Fig. 4. The test track is suitable for repetitive tests and often applied for suspension system evaluation\textsuperscript{[5,17]}. The track is as well a part the standard road for evaluation of seat for approval of agricultural and forestry vehicles\textsuperscript{[18]}.

Figure 4: ISO 5008 Smooth Track.
The travel speed for all tests is kept constant at 17.5km/h. All test are conducted according to the recommendations by the EN 1032 standard for vibration test of mobile machinery\textsuperscript{[19]}. The active oscillation damping is tested for two different implement configurations of the tractor, Tab. 1. Both configurations are tested with and without applied damping minimum five (5) times in order to determine a statistical mean. The data is post analyzed by a MATLAB script.

**Table 1:** Different implement configuration of the tractor.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>w/o AD</th>
<th>with AD</th>
<th>w/o AD</th>
<th>with AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front implement mass [kg]</td>
<td>3.400</td>
<td>1.800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front tire inflation pressure [bar]</td>
<td>2.0</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear implement mass [kg]</td>
<td>6.260</td>
<td>2.200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rear tire inflation pressure [bar]</td>
<td>2.0</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Results**

The root-mean-square pitch acceleration for the two implement configurations are shown in Tab. 2 without active damping (AD) enabled and with AD enabled for both front and rear hitch. For the heavy rear implement a reduction of 25% is obtained with active damping enabled, and for the plough due to the higher mass moment of inertia contribution a reduction of 32% is obtained.

**Table 2:** Comparison of pitching oscillation with and without active damping.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>w/o AD</th>
<th>with AD</th>
<th>w/o AD</th>
<th>with AD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samples $\omega_{RMS,y}$ [rad/s$^2$]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>#1</td>
<td>0.386</td>
<td>0.305</td>
<td>0.431</td>
<td>0.289</td>
</tr>
<tr>
<td>#2</td>
<td>0.429</td>
<td>0.301</td>
<td>0.416</td>
<td>0.277</td>
</tr>
<tr>
<td>#3</td>
<td>0.452</td>
<td>0.295</td>
<td>0.431</td>
<td>0.282</td>
</tr>
<tr>
<td>#4</td>
<td>0.392</td>
<td>0.298</td>
<td>0.412</td>
<td>0.284</td>
</tr>
<tr>
<td>#5</td>
<td>0.384</td>
<td>0.313</td>
<td>0.418</td>
<td>0.281</td>
</tr>
<tr>
<td>Mean</td>
<td>0.409</td>
<td>0.303</td>
<td>0.422</td>
<td>0.283</td>
</tr>
<tr>
<td>Reduction</td>
<td>25%</td>
<td></td>
<td>32%</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5 shows the recorded pitch acceleration in time domain for one measurement with and without active damping for the tractor with the plough implement. It is observed that the amplitudes with active damping in general are smaller. A FFT analysis of the data will reveal a dominant frequency of 1Hz.

The improvement of ride comfort in terms of reduction of the root-mean-square pitch acceleration, Tab. 2, is in accordance with the subjective improvement reported by several CLAAS test drivers. In addition to above, high speed test at on-road conditions have been carried out with the same set of control parameters for the active damping and showed a reduction of pitch oscillations of 25%.

**Conclusion**

In this paper, a comfort evaluation method for pitching oscillation damping of agricultural tractors is proposed and demonstrated in a full scale implementation of active damping of the electro-hydraulic hitch control. The method turns out to be a suitable way of quantifying ride comfort in terms of pitch oscillations. The method can be applied of all mobile machines for evaluation of pitch oscillations, it is easy to instrument and the data analysis is straight forward; most data acquisition software package facilitate the needed filters and calculations. The evaluation method, though, is sensitive to the duration, and the dynamics is sensitive to tire inflation pressure and travel speed. Hence, it is recommended to follow the guidelines by EN 1032, apply cruise control and be strict on timing for any benchmark test.
Bibliography


[19] EN 1032 Mechanical Vibration - Testing of mobile machinery in order to determine the vibration emission value (2003), European Committee for Standardization.