# ALIGNMENT OF 6-DOF WHOLE-BODY VIBRATION DATA

[1,2]Robert J. Jack, [1,2]Michele Oliver, [2]Robert Dony
[1] *Biophysics Interdepartmental Group, University of Guelph, Guelph ON*
[2] *School of Engineering, University of Guelph, Guelph ON*

## INTRODUCTION

Occupational exposure to seated whole-body vibration (WBV) has been associated with a variety of health problems including low back pain [1][2][3][7][13]. The occurrence and severity of these health complaints can be linked to WBV exposure levels [1][2][8] and the postures adopted by the operators while being exposed to WBV [10][13][18]. Although this association has been made, there has been little investigation into the interactive effects of posture and WBV exposures.

The lack of 6-degree-of-freedom (6-DOF) exposure data sets available at the operator/seat interface (OSI) and vehicle chassis is another concern. Field studies used to discern the health effects associated with WBV exposure for health guidelines are limited to translational WBV exposures, but rotational vibration may have an impact on operator health [9]. Thus, further investigations into the effects of 6-DOF WBV on health are necessary. The lack of comprehensive 6-DOF field data also limits the effectiveness of vehicle seat designs. Equipment manufacturers utilize suspension seats to attenuate WBV exposure levels in an attempt to improve operator comfort and reduce operator injuries related to WBV exposure. The lack of 6-DOF chassis WBV field data sets available for use as inputs while tuning the dynamic response of these seats undoubtedly result in less effective seat designs.

The field investigation deficiencies outlined above are partly due to the use of equipment with limited measurement capabilities. The limited memory and available channels for data collection with most data logging systems has resulted in a lack of simultaneous 6-DOF WBV measurements on a vehicle chassis and OSI, coupled with simultaneous measurements of operator posture. Comprehensive studies of this nature usually need to utilize more than one data logging system [4]. Here, a time stamp must be applied so that the data time histories of the two different systems can be aligned. This type of alignment reduces the channels available for data collection as one channel from each data logger is required for the time stamp. This desire has led these researchers to develop a multiple resolution cross-correlation (MRXcorr) procedure to align 6-DOF WBV data sets collected at the chassis and OSI of mobile forestry machinery. The MRXcorr utilizes selected multisensor data fusion techniques used in military target tracking and autonomous robotics [16]. In particular, concepts used to deal with out-of-sequence (OOS) data and multiple resolutional filtering are used.

In multisensor tracking systems, the data from each sensor is received with its own discrete timestamp, but there are various pre-processing and propagation times, as well as different onsets of data collection from the different sensors resulting in some data arriving OOS (i.e., with a time lag) [11][16]. As a consequence of time discrepancies, several forward and backward prediction algorithms have been created for the online processing of OOS data [6][11][12]. The MRXcorr presented here is designed for post processing but still predicts and aligns data time histories from multiple sensors, much like the aforementioned algorithms.

The MRXcorr also utilizes multiple resolutional filtering, which allows data to be viewed with combinations of different levels of resolution [16]. Here, the MRXcorr uses a large amount of low resolution data for an initial alignment of the data, and then progressively higher frequency data is added back to the original signal over a small specifically selected data window to improve the accuracy of the alignment. This division of labor between processing levels has been shown to give improved performance, especially in environments with high background noise levels [16]. In addition, with less data available at the lowest level, the computation time is decreased [16].

This paper explores the capabilities of the MRXcorr for the alignment of simultaneously collected WBV data sets collected at the chassis and OSI, and validates its use.

## METHODS

### MULTIPLE RESOLUTION CROSS-CORRELATION PROCEDURE

Initially, all data were low-passed filtered with a cut-off frequency that was 1.5 times the upper bandwidth of the sensors used to attenuate high-end noise. A Discrete Fourier Transform (DFT) was then performed on an initial 300,000 data point window at the start of each 6-DOF data set. The upper limit of the frequency spectrum for the initial window of data was determined from the DFT. The initial window of data was then low-pass filtered with the cut-off frequency set to the upper limit of the previously determined low frequency signal range. This low-passed data was then resampled at a rate that was 2n+1 that of the cut-off frequency used for the low-pass filter. A cross-correlation (Xcorr) was then conducted between the two channels of low passed data that measured the same axis (i.e., that measured accelerations in the X-axis on the chassis and OSI) for all six pairs of channels collected. The original data set was then shifted by the phase lag between the two data sets, as determined from the low resolution Xcorr.

The aligned low resolution data was then windowed (1,000 to 5,000 data points) where a high frequency signal was expected (i.e., while the vehicle was idling between start-up and the onset of driving). While idling, a vehicle should display high frequency engine noise in the range of 15-40Hz (based on idling rpm data reported in several manufacturer vehicle specification sheets) for both the chassis and OSI vibration measurements in the X- and Y-axes since seats are not designed to dampen vibrations in those axes. Griffin [5] reports that X- and Y-axis vibration through the squab of a conventional seat can be near unity. The window should also contain some low frequency signal to ensure that the low resolution Xcorr shift is maintained while higher resolution cross-correlations (Xcorrs) provide small adjustments to the previous alignment. The low frequency signals however, must be similar between the channels measuring the same axes. This is done to minimize the discrepancies between the OSI and chassis due to the operator moving. If the low frequency signal produced by the movement of the operator is not minimized, the Xcorrs may provide an improper phase lag estimate for signal alignment.

Another DFT was then conducted on the small window of low resolution aligned data to determine the frequency range for the two new data set windows. The windowed data were then low-passed filtered with the cut-off frequency set to the upper limit of the aforementioned frequency range. The low-passed data was then resampled at a rate that is 2n+1 that of the cut-off frequency used for the low-pass filter. Xcorrs were then conducted between the two channels that measured the same axis for all six channel pairs. The low-resolution shifted data set was then shifted by the phase lag between the two higher frequency content/higher resolution data sets, as determined from the Xcorr. Here, X- and Y-axes are given priority since they typically are the least affected by the seat dynamics as outlined earlier. The higher frequency content data is continually resampled at a higher sample rate (i.e., the rate is doubled with each iteration) and shifted until the original sample rate is achieved. This results in a time history alignment at the original sample rate.

## MULTIPLE RESOLUTION CROSS-CORRELATION PROCEDURE VALIDATION

Three validation tests were conducted to substantiate the use of the MRXcorr procedure.

### Test 1

A 6-DOF data set was aligned with an identical data set that had been altered to contain a known data point shift. A comparison of the known data point shift to the shift determined from the MRXcorr was then conducted to determine the MRXcorr's accuracy in predicting the known data shift.

### Test 2

The same comparison of identical 6-DOF data sets with a known data point shift as in Validation 1 was conducted. However, here a series of zero-lag Butterworth band-pass filters, signal gains, and random noise were used to alter the shifted data set such that its frequency content resembled that of actual 6-DOF seat data relative to the 6-DOF chassis input. This was done to simulate differences one would see between a vehicle chassis and OSI 6-DOF data sets due to seat dynamics and operator movements while eliminating any unknown phase shifts that the seat may produce since the zero-lag Butterworth filters have a linear zero-phase [17]. Once again, the induced shift was compared to the shift ascertained by the MRXcorr procedure to determine if the MRXcorr accurately predicted the known data shift.

### Test 3

Finally, the MRXcorr alignment procedure was applied to a real 6-DOF WBV data set collected on the chassis and OSI of a forestry skidder. Here, there is an unknown delay between the onset of data collection between the two data sets. The alignment determined by the MRXcorr was compared to a Xcorr conducted on the entire data set. The comparison was done both visually and by means of a regression analysis performed between the two data sets to determine which line-up method resulted in time histories with greater $r^2$ values.

## RESULTS

### TEST 1

The MRXcorr precisely determined the known phase shift between two identical 6-DOF data sets. Here, a randomly selected 13,286 data point shift was applied to one of the 6-DOF data sets. The MRXcorr indicated that the exact same 13286 data point shift was necessary to align all 6-DOF data sets.

### TEST 2

The MRXcorr precisely determined the 13,286 data point shift between the initial signal and the identical signal which was altered to resemble seat WBV signals in the X-, Z- and Yaw axes. In the Y-, Roll and Pitch axes it was found that the data sets were misaligned by one data point, which corresponded to a time history misalignment of 0.002 seconds.

### TEST 3

Finally, the MRXcorr alignment procedure was applied to actual field 6-DOF WBV data sets collected at the chassis and OSI of a forestry skidder. A data shift of 50,485 data-points was determined using the MRXcorr alignment procedure, where a shift of 50,459 data-points was determined using an Xcorr. When observing the aligned time histories, the MRXcorr aligned data time histories and the Xcorr time histories displayed similar patterns. However, the MRXcorr alignment did appear to be aligned better as evidenced by the fact that the $r^2$ values from a correlation between the two data sets for the initial 600s and an arbitrary 5s window of data were both greater when aligned with the MRXcorr alignment procedure (Table 1).

Table 1: Comparison of the $r^2$ values from correlations of between seat and chassis data aligned using the multiple resolution cross-correlation (MRXcorr) and a cross-correlation (Xcorr) for the initial 600s of a data set and an arbitrary 5s window of data.

| **Axes** | **MRXcorr** | | **Xcorr** | |
|---|---|---|---|---|
| | ***0s – 600s*** | ***190s – 195s*** | ***0s – 600s*** | ***190s – 195s*** |
| X | 0.910 | 0.820 | 0.876 | 0.505 |
| Y | 0.850 | 0.863 | 0.750 | 0.328 |
| Z | 0.465 | 0.396 | 0.144 | 0.107 |
| Roll | 0.504 | 0.377 | 0.368 | 0.265 |
| Pitch | 0.535 | 0.685 | 0.392 | 0.531 |
| Yaw | 0.960 | 0.860 | 0.950 | 0.626 |

## DISCUSSION

The MRXcorr technique presented here is simply a series of Xcorrs that on their own can accurately predict a data shift between two identical signals. What needs to be considered here is the fact that the two signals which are being aligned are not identical. The chassis signal is the input to the seat, but the dynamics of the seat suspension system and cushioning, as well as the movements of the operator on the seat alter that signal. The result is two similar but not identical signals. The power of the MRXcorr technique is that its windowing constraints are designed to address these elements of signal distortion so that the effects of operator movement and seat dynamics are minimized. For example, the onset of engine start-up and initial idling prior to the onset of the forward progression of the machine was chosen because it is known than any low frequency movement would be the result of the operator moving and not terrain induced signal from driving. As well, while idling, high frequency engine noise is a more dominant signal than when the vehicle is being driven, thus this high frequency signal can now be used during the high resolution shift adjustments to accurately align the two signals. It should be noted though that the procedure requires the initial onset of forward progression to be included. If only the engine noise signal is used, the Xcorr utilized by the MRXcorr will look for the best fit for the data in the window analyzed. This could result in a seemingly arbitrary shift when considering the entire data set. Maintaining some of common low frequency driving signal for the chassis and OSI will allow the previous low frequency shift to be maintained, resulting in only a fine adjustment to the signal alignment during the higher resolution alignments.

The initial validation tests conducted in this paper were designed to evaluate whether the MRXcorr could accurately predict a know data shift. Of particular concern was whether or not the MRXcorr could predict a known data shift when the datasets were not identical. These questions were answered in Tests 1 and 2. In both instances the MRXcorr was able to predict the induced data shifts. The ability to predict the data shift when the signals resembled field OSI and chassis 6-DOF WBV signals, lends great support for the MRXcorr's ability to align complex field vibration measurements. This is further substantiated by the fact that the MRXcorr performed better than another simple alignment technique (Xcorr) as demonstrated by Test 3.

The ability to align simultaneously collected 6-DOF WBV data sets collected on the chassis and OSI will allow researchers to determine seat dynamics under field conditions. The dynamic seat responses determined in the field can then be compared to laboratory studies to substantiate the laboratory results and validate the conclusions. As well, representative field data for chassis exposures will provide researchers with an accurate input for dynamic seat testing which can be used to investigate and optimize 6-DOF transmission characteristics for a seat in a laboratory setting. Two studies have measured both OSI and chassis vibrations levels, however, these studies did not collect the OSI and chassis data simultaneously [15][14]. As a result, cross spectral density calculations were used to determine seat transfer functions with no phase information. If the OSI and chassis data had been collected simultaneously via the same measurement system, the phase information could have been calculated. Researchers may find it difficult and costly to obtain a measurement system with the necessary twelve channels. The application of the MRXcorr process as outlined in this paper will allow researchers an alternative method to acquire aligned WBV data. Our MRXcorr allows researchers to collect the OSI and chassis WBV data with two separate measurement systems and then combine the data later. Like the cross spectral density approach mentioned earlier, the MRXcorr process does not allow one to determine precise phase lags for transfer functions. One can however, determine phase lags between different axes if they are normalized to an axis of interest. In addition, unlike the cross spectral density method discussed above, the MRXcorr enables one to create time histories of aligned data that can be used as OSI and chassis inputs during laboratory investigations into WBV and health, comfort, and seat dynamics. As well, the aligned time histories can be windowed to determine transfer function and WBV exposure magnitudes for specific instances in time.

Another benefit of this MRXcorr technique is the fact that it only uses a portion of a very large data set. As a result, less computer memory is required and the program takes less time to run. These authors found that some of the data files collected were too large to run an Xcorr, despite the 1.0GB of RAM available in the analyzing computer.

## CONCLUSION

The MRXcorr here was proven to accurately align identical 6-DOF WBV data sets and a simulated 6-DOF OSI WBV data set with its chassis counterpart. As well, the specific considerations that the MRXcorr technique affords to the alignment of chassis and OSI WBV signals have proven to make the technique more accurate than an Xcorr between the two data sets. Therefore, the MRXcorr procedure is a viable means of aligning OSI and chassis WBV data signals collected from different data loggers. The ability of the MRXcorr to align the complex data sets in this paper suggests that its a promising technique which could be applied to other biomechanical data sets involving multiple data collection systems.

## REFERENCES

[1] D.J. Bottoms, and T.S. Barber, “A swiveling seat to improve tractor drivers' posture,” *Appl Ergon*, 9(2), 77-84, 1978.

[2] M. Bovenzi, and A. Betta, “Low-back disorders in agricultural tractor drivers exposed to whole-body vibration and postural stress,” *Appl Ergon*, 25(4), 231-241, 1994.

[3] M. Bovenzi, and C.T.J. Hulshof, “An updated review of epidemiologic studies on the relationship between exposure to whole-body vibration and low back pain,” *J Sound and Vib*, 215, 595-611, 1998.

[4] S. Cation, R.J. Jack, J. Dickey, N. Lee Shee, and M. Oliver, “Six degree of freedom whole-body vibration exposure during forestry skidder operations,” *submitted to IJIE, 2007.*

[5] M.J. Grifiin, *Handbook of human vibration*. Academic Press Ltd. San Diego, CA, 1990.

[6] R.D. Hilton, D.A. Martin, and W.D. Blair, *Tracking with time-delayed data in multisensor systems*, Naval Surface Warfare Center, Dahlgren, VA, 1993.

[7] C. Hulshof, and B.V. van Zanten, “Whole-body vibration and low-back pain: A review of epidemiological studies,” *Int Arch Occup Environ Health*, 59, 205-220, 1987.

[8] IS0 2631-1, *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration-Part 1: General requirements*, International Organization for Standardization, Geneva, Switzerland, 1997.

[9] R.J. Jack, and M. Oliver, “A review of factors influencing whole-body vibration injuries in mobile forest machine operators,” *submitted to Int J Forest Eng*, 2006.

[10] M.L. Magnusson, M.H. Pope, D.G. Wilder, and B. Areskoug, “Are occupational drivers at an increased risk for developing musculoskeletal disorders?” *Spine*, 21, 710-717, 1996.

[11] M. Mallick, S. Coraluppi, and C. Carthel, “Advances in asynchronous and decentralized estimation,” *IEEE*, 0-7803-6599-2, 2001.

[12] E.W. Nettleton, and H. Durrant-Whyte, “Delayed and asequent data in decentralized sensing networks,” *Proc SPIE Conf,* 4571, 1-9, 2001.

[13] NIOSH 97-141, *Musculoskeletal disorders and workplace factors: A critical review of epidemiologic evidence for work-related musculoskeletal disorders of the neck, upper extremity, and low back*, National Institute for Occupational Safety and Health, Cincinnati, OH, 1997.

[14] K.C. Parsons, E.M. Whittham, and M.J. Griffin, “Six axis vehicle vibration and its effects on comfort,” *Ergonomics*, 22(2), 211-225, 1979.

[15] C.C. Smith, and Y.K. Kwak, “Identification of the dynamic characteristics of a bench-type automotive seat for the evaluation of ride quality,” *J Dyn Meas and Cont*, 100, 42-49, 1978.

[16] D. Smith, and S. Singh, “Approaches to multisensor data fusion in target tracking: A survey," *IEEE Trans Knowl Data Eng*, 18(12), 1696-1710, 2006.

[17] S.W. Smith, *The Scientists and Engineers Guide to Digital Signal Processing 2nd Ed*, California Technical Publishing San Diego, California, 1999.

[18] J. Village, J. Morrison, and D. Leong, “Whole-body vibration in underground load-haul-dump vehicles,” *Ergonomics*, 32(10), 1167-1183, 1989.