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DYNAMIC CALIBRATION OF A BUS

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Abstract − In this study we present a dynamic calibration of an automobile bus. The characterization consists of measuring the vertical acceleration signals during passage over a short bump. Non-parametric identification is then adopted to determine digital 'vehicle' filters, which mimics the dynamic behavior of the bus. Such filters are required for performing our earlier presented synthesis and analysis of speed limiting road humps. The combination of these methods provides a complete set of unprecedented tools for analyzing existing humps, as well as finding their optimal profile.

Keywords: dynamic calibration, bus, road hump

1. INTRODUCTION

Road humps [1] are nowadays used extensively to enforce speed limits in the traffic. At present, there are surprisingly no widely accepted quantitative methods [2] to design these humps, except by means of trial-and-error and repeated measurements. The *variation* of vehicle response with speed is the target function for road hump construction, as this imposes the speed reduction. The response of the vehicle has a fairly complex variation with velocity and there are many different types of vehicles and hump profiles. The evaluation and optimization of road humps is therefore non-trivial.

Recently [3,4], we proposed methods to analyze and optimize road humps. The optimum was defined by a desired response of a given typical vehicle running at the speed limit. In these studies, a harmonic acceleration profile was chosen. The methods were based on digital filtering of the height profile of the hump. To synthesize these filters, information about the vehicles is required. The accuracy of the vehicle models is not, however, of primary interest as they should be typical rather than specific for individual vehicles. A large variation of vehicles, regarding types (buses, cars etc.) and age etc., running on every road is an unquestionable fact which motivates the use of rather coarse models. Relevant and sufficiently accurate information about the vehicles may thus be obtained in several ways: The vehicle manufacturer can for instance supply information about typical stiffness etc. Another option that will be exploited here is to 'calibrate' typical vehicles of interest: The road height variation is converted to a 'signal' when the hump is passed at a given velocity. This signal is realized by means of a geometric profile and speed of vehicle and is thus traceable to measurements of length and time. If the bus contains indicators of height, a relation can thus be established between the road hump profile with measurement uncertainty provided by measurement standards, and the corresponding indicated heights of the bus with associated measurement uncertainties. In the widest sense, a dynamic calibration [5] of the bus can thus be performed. As good performance is not required for any device to qualify for a calibration, it is irrelevant that the bus will not 'measure' the hump very well in practice. The procedure of calibration to be presented here will closely resemble traditional dynamic characterization and includes non-parametric system identification. As the variation of vehicles in the traffic results in a much larger variation than the estimated accuracy of calibration, the measurement uncertainty will be omitted from the discussion even though it could be evaluated.

2. DYNAMIC CALIBRATION

2.1. Characterization – the measurement

The dynamic characterization was performed at Hunan University of Science and Technology in Xiangtan, Hunan province of China. A school bus was run over a short road bump while the acceleration was measured at two distinct positions, in the front and the rear part of the bus, as shown in Fig. 1. The measurement system consisted of two piezoelectric accelerometers (YD61 series) and one signal analyzer (Nicolet Odyssey2.0).The velocity had to be intermediate to provide a complete but also simple dynamic analysis: The speed should be high enough to provide sufficient bandwidth of the test signal, which is required for a complete characterization. The speed should also be limited not to mix the front and rear axle responses too much. The ideal speed for this type of vehicle calibration should be determined from the correlation times of the responses set by the vehicle stiffness and the axle separation, and length of the road hump. A short hump/bump is preferable for maximizing the calibration bandwidth as it separates the front and rear axes responses as much as possible.

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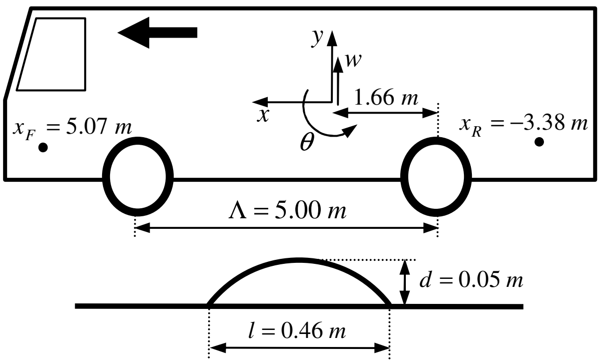

Fig. 1. Bus with sensors and exciting road bump. The front and rear accelerometer positions x_F and x_R are relative to the center-of-mass at $x = 0$. The hump profile is a circular arc.

The measurement used for the dynamic calibration is shown in Fig. 2. As is seen, the velocity was chosen as high as possible avoiding significant mixing of front and rear axle responses. No measurements of wheel accelerations were made as only the total response of the bus to the hump profile is important for the hump analysis.

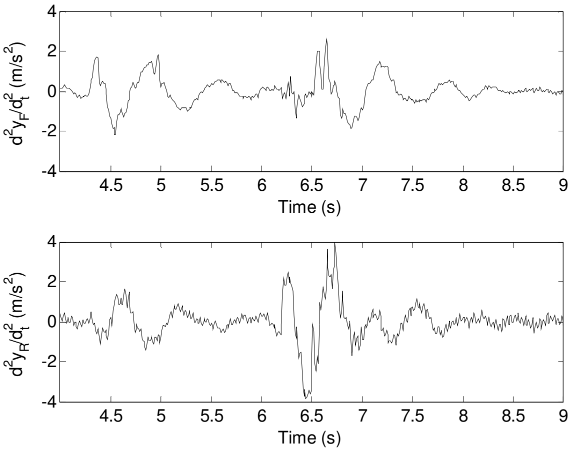

Fig. 2. Measured signals with the front (top) and rear (bottom) accelerometers, for the speed $v = 9.6\ \mathrm{km/h}$.

2.2. Pre-processing

The measured signals (Fig. 2) contain a large amount of noise generated by unknown excitations, such as engine vibrations and unevenness of the road. These are not included in the model of the measurement. Careful pre-processing is thus required in order to extract the appropriate signal and obtain a reasonable bus model in the process of identification.

(1) The vertical acceleration at measured positions is first transformed to center-of-mass translation w and normalized rotation $\Lambda\theta$, see Fig. 1.

$$\begin{pmatrix} \ddot{w} \\ \Lambda\ddot{\theta} \end{pmatrix} = \frac{1}{|x_F| + |x_R|} \begin{pmatrix} |x_R| & |x_F| \\ -\Lambda & \Lambda \end{pmatrix} \begin{pmatrix} \ddot{y}_F \\ \ddot{y}_R \end{pmatrix}. \tag{1}$$

(2) Two differentiations are included when measuring acceleration and not displacement. There are at least three reasons for excluding these trivial operations from the transfer function: 1. The accuracy of identification will increase as the order is reduced. 2. The level of noise will be reduced. 3. The transfer function will be unit-less. A digital integration filter was therefore applied twice to the measured acceleration. It was obtained using the bilinear transformation [6] of the ideal integrator $H_I(s) = s^{-1}$,

$$G_I(z) = T_S \frac{z+1}{z-1}. \tag{2}$$

Most importantly for the analyses of pulse signals, this filter has the correct phase, but also accurate low frequency properties and large high frequency (noise) attenuation.

(3) A minor constant offset of the measured acceleration will result in an error of w and $\Lambda\theta$ increasing in time. Detrending is thus required. The extracted signals were therefore chosen to correspond to equal displacements at the end points (estimated by inspection). This condition was then enforced by subtracting a constant corresponding to a constant erroneous offset of measured acceleration.

2.3. Identification – dynamic vehicle filters

The dynamic model of the bus is conveniently described by the vehicle displacement 2x2 transfer function matrix $H_{\mathrm{BUS}}(s)$. It propagates the front and rear road height signals to the center-of-mass displacement w and rotation $\Lambda\theta$,

$$\begin{aligned} H_{\mathrm{BUS}}(s) &= \begin{pmatrix} H_{WF} & H_{WR} \\ H_{\theta F} & H_{\theta R} \end{pmatrix} \\ \begin{pmatrix} W \\ \Lambda\theta \end{pmatrix} &= H_{\mathrm{BUS}}(s) \begin{pmatrix} 1 \\ \exp(-\tau s) \end{pmatrix} Y(s) \end{aligned}. \tag{3}$$

The front $y(t)$ and rear road height signals $y(t-\tau)$ are equal. The identified delay τ will be used to determine the velocity for each measurement, $v = \Lambda/\tau$. This is required to transform the measured geometric road hump profile to the input calibration time signal. The reference signal was thus determined from a simple geometric measurement of the calibration bump and identified time delay. For the analysis of road humps it is sufficient to know the four digital filters $G_{mn}(z),\ m = \{W,\theta\}, n = \{F,R\}$ corresponding to the continuous time matrix elements of $H_{\mathrm{BUS}}(s)$. These filters must however be known separately for the different individual responses in order to study the principle of operation of road humps, i.e. the dependence of hump response on vehicle velocity. One realization of the filters will here be directly synthesized from the calibration measurement. The derivation of these filters we regard as a type of non-parametric system identification [7] devised for road hump analysis. The precision and uncertainty of the filters are, as already mentioned in the introduction, of minor importance and will be excluded from the discussion.

The filters were synthesized by a technique similar to the impulse invariance mapping of parameterized transfer functions [6]: The vehicle *impulse* responses are first found from the measured vehicle *road hump* (Fig. 1) response by means of a bump de-convolution filter g_{BUMP}^{-1}. The impulse responses are then sampled and scaled to the actual sampling rate to give the coefficients of the four digital FIR vehicle filters G_{mn}. The length of these filters will be of order σf_S, where σ is the decay time for the vibrations. Typically, a couple of hundred coefficients are required for appropriate sampling rates. As an option, the length of these filters may be strongly reduced by means of parametric time domain system identification using IIR models motivated by the design of the vehicle [4]. This is desirable for understanding the construction of the bus but irrelevant for the hump analysis [3,4]. The de-convolution of measured displacement was made in the time domain and the filter G_{BUMP}^{-1} was like G_{mn} also derived from a sampled impulse response:

1. For the velocity determined from the calibration measurement, the bump profile versus time was sampled to find the convolving impulse response g_{BUMP} of the measurement.
2. The transfer function G_{BUMP} is marginally stable and thus has zeros on the unit circle $|z_k| = 1$. It is regularized by the invoking the approximation $1/G_{\mathrm{BUMP}} \approx \left(1/G_{\mathrm{BUMP}}^{D} + 1/G_{\mathrm{BUMP}}^{R}\right)/2$, valid except in the vicinity of the points of irregularity $z = z_k$. The prototype de-convolution filters $1/G_{\mathrm{BUMP}}^{D}$ and $1/G_{\mathrm{BUMP}}^{R}$ have poles $(0 < \varepsilon << 1)$ $p_k = z_k/(1+\varepsilon)$ and $p_k = z_k(1+\varepsilon)$, respectively.
3. A stable robust de-convolution filter is found by adapting $1/G_{\mathrm{BUMP}}^{D}$ for direct and $1/G_{\mathrm{BUMP}}^{R}$ for time-reversed filtering, each including a low-pass noise filter [8].

After de-convolution there is at least one important constraint on each impulse response. The required static amplification given by the sum of the filter coefficients is easily found from the geometry of Fig. 1. In addition to the constant offset already accounted for (step 3 in section 2.2) there may be an unknown small time-dependent offset. This will here be amplified due to the zero frequency divergence of (double) integration. The derived response will then contain an integrated time-dependent error and thus needs adjustment, in order to have correct static amplification. A plausible offset function with as slow variation as possible was therefore be added as the final step to get physically sound filters. As the impulse responses to ideal impulses are of a theoretical character, the corresponding step responses are instead shown in Fig. 3.

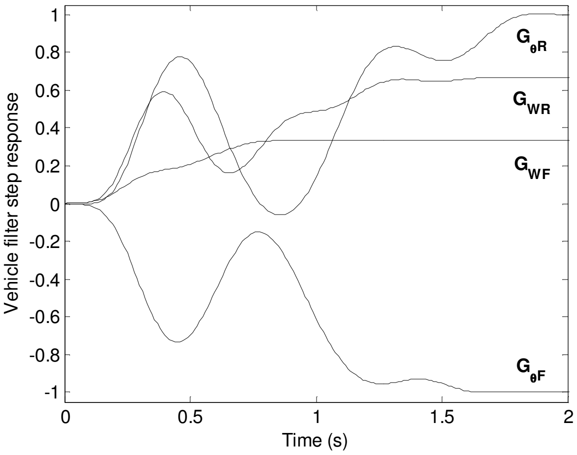

Fig. 3. Step responses of derived vehicle filters.

3. CONCLUSIONS

A method for impulse calibration of vehicles is proposed. This method complements previous studies on analysis of speed limiting road humps. Calibration is required when vehicle models are not known or can be estimated by other means. Presumably, the gain in simplicity and reduced cost dominates the loss in accuracy when characterizing vehicles using existing road bumps as here, instead of large and complex heavy duty specialized vehicle calibration facilities.

By repeating the suggested calibration scheme for many vehicles a complete filter bank can be found, which allows for studying all the different hump responses of the actual traffic. Together, these methods provide a complete set of tools for determining and optimizing the properties of speed limiting road humps used all over the world.

ACKNOWLEDGMENTS

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REFERENCES

[1] B. Engwall, “Device to prevent vehicles from passing a temporarily speed-reduced part of a road with high speed.” United States Patent 4135839, 1979.

[2] ITE Technical Council Task Force on Speed Humps, “Guidelines for the Design and Application of Speed Humps,” Washington, D.C., USA: ITE Institute of Transportation Engineers, 1997 and 2007.

[3] P.Y. Zhu, J.P. Hessling, D.S. Liu, “Optimal road hump for comfortable speed reduction”, *4th ISPMM’ 2008, International Symposium on Precision Mechanical Measurements*, Anhui, China, Aug. 25-29, 2008.

[4] J.P. Hessling, P.Y. Zhu, “Analysis of Vehicle Rotation during Passage over Speed Control Road Humps”, *ICICTA 2008, International Conference on Intelligent Computation Technology and Automation*, Changsha, China, Oct. 20-22, 2008.

[5] International vocabulary of metrology – basic and general concepts and associated terms (VIM), BIPM, JCGM 200:2008 (E/F).

[6] Chen Chi-Tsong *Digital Signal Processing*, Oxford University Press, New York, 2001, ISBN 0-19-513638-1.

[7] L Ljung *System Identification: Theory for the User*, Prentice Hall, 2nd Ed, 1999.

[8] J.P. Hessling, "A novel method of dynamic correction,", Meas. Sci. Technol., **19**, 075101, 2008.