MODELING AND SIMULATION OF BLAST WAVE FOR PRESSURE SENSOR DESIGN

[1]B.S. CHAURASIA, S. TANDON, S. SHUKLA, P. MISHRA, ANAND MOHAN AND S.K. BALASUBRAMANIAN

[1]Department of Electronics Engineering,
Institute of Technology, Banaras Hindu University, Varanasi, India
bhanu_chaurasia@yahoo.com

Abstract:

In this paper a universal model for pressure waves generated by high energy charge explosives and gunshots is developed for determining the pressure vs. time profile (P-T curve) at a given point in space which is useful for design and characterization of pressure micro sensors and explosives etc. The simulation of the model is carried out through virtual instrumentation (VI) using LabVIEW. The technique used to develop the model, in the present work, is similar to the well known statistical technique of structural equation modeling (SEM).The simulated data is compared with the available experimental data sets in terms of Pearson's correlation and chi-squared goodness-of-fit test (χ^2) and they were found to be in close matching. This work can be extended for modeling and characterization of other types of pressure waves.

Keywords: Goodness-of-fit, Interactive modelling, Pearson's correlation, Pressure model, Virtual instrument.

1. INTRODUCTION

Characterization of blast waves generated by explosion finds important application in safety assessment of mines and military environment and this is done by recording the generated pressures at different locations and times using *pressure sensors*. These sensors when being designed using MEMS CAD software can well be characterized by the use of blast wave models as transient input stimulus to the sensor through simulation. Further, as the pressure generated by the blast waves dynamically varies with time at a point in space, their accurate modeling becomes a challenging task. Although the pressure-distance relationship of waves due to explosion has been extensively studied [1]-[3], but the variation of pressure with time which is invariably needed for understanding the dynamics of the blast waves is relatively less explored [4]. Such realistic modeling of pressure time relationship of blast waves is essential for estimating the intensity of blast pressure waves at a given space coordinate and at a specific time to carry out safety operation sand also; such models can be useful for applying it as input to a sensor and characterize its response. Therefore accurate modeling of pressure time variation of blast waves is an interesting problem which has been investigated under the present study.

This paper describes development of a new model for the pressure time variation of blast waves at a fixed coordinate in space. The model is simulated using *LabVIEW* and the model parameters are characterized [5] - [7] through an iterative process to achieve the best match between the known pressure time plot and simulated response. The developed model has been validated by comparing the blast pressure waveform generated by simulation with the plot of real time explosion data of high energy charge and gunshot explosions. The approach used for modeling and validating the pressure-time curve for blast wave is similar to the structural equation modeling (SEM) technique [8]. In this Pearson's correlation and Chi- squared (χ^2) goodness-of-fit tests are applied to compare the data obtained through simulation and the experimental one and Minitab 15® used to generate the test reports. The results show a high degree of correlation between various sets of experimental and modeled data, along with the goodness-of-fit satisfied, as summarized in section 4.

The proposed technique can be further extended to model seismic and underwater acoustic waveforms.

2. BLAST WAVE MODELLING

The pressure profile generated by an ideal blast wave at a location away from the center of explosion has been approximated as shown in figure 1 [9] where the initial pressure is the ambient pressure p_o before the shock wave front reaches the given point. At time $t=t_a$, the pressure rises discontinuously to the peak value ($p_o + P_s^+$), where P_s^+ is the peak overpressure and decays to the ambient pressure in a time T^+, which is referred as positive phase. Then the pressure drops to a partial vacuum of value ($p_o - P_s^-$) and returns to the ambient in a time T^- referred as negative phase.

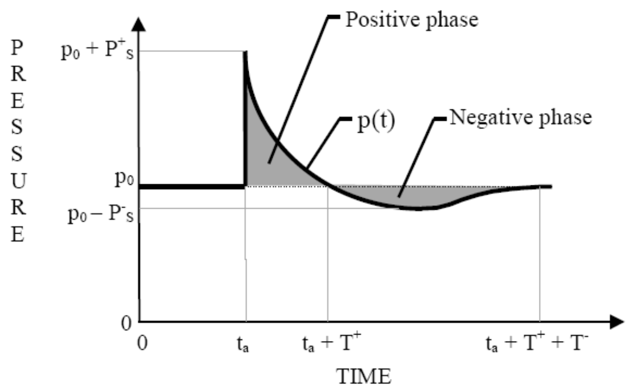

Figure1. Pressure-time (*P-T*) curve of an ideal blast

The pressure profile curve *p(t)* can be approximately described by the modified Friedlander equation [10] as below.

$$p(t) = p_o + P_s^+ (1 - t/T^+)\, e^{-bt/T+} \qquad (1)$$

where, time t is measured from time of arrival t_a. The blast wave parameters P_s^+, t_a, T^+ and b can be varied to customize the pressure time profile curve and the initial decay rate for different explosions. Although equation (1) gives simple model for the blast wave profile which is computationally simple but it is less accurate and does not model the transient part and different types of waveforms.

Also, in recent works [3], [4], [11] last wave profiles that are closer to experimental or theoretical models have been developed but in a real-time simulation, those models involve more computational complexity and higher costs.

2.1. The proposed model

The proposed blast wave model conserves the simplified structure as in equation (1) and also obviates the need of intense computation. The *pressure-time* '*p(t)*' equation is the combination of simplified physical equations and experimental data, and is developed using LabView to model and simulate the waveform. Before discussing the technique used in the present work, it is quite pertinent to mention here about the structural equation modeling (SEM) which follows a logical sequence of five steps or processes [8] as given below.

Model Specification involves using all the available relevant theory, research and information and developing a theoretical model.

Model Identification answers the question: on the basis of the sample data can a unique set of parameter estimates be found? Model Identification depends on the designation of parameters as fixed, free or constrained.

Model Estimation includes examining different methods for estimating the parameters, i.e., population parameters in a structural equation model. We want to obtain estimates for each of the parameters specified in the model that produce the implied matrix E such that the parameter values yield a matrix as close as possible to our sample covariance matrix S of the observed or indicator variables.

Model Testing follows once the parameter estimates are obtained for a specified SEM model. In this step the applied researcher should determine how well the data fit the model. In other words, to what extent is the theoretical model supported by the sample data obtained.

Model Modification is required if the fit of the implied theoretical model is not as strong as one would expect (like the one with an initial model) and it becomes necessary to modify and subsequently evaluate the model. The SEM techniques can be further classified into *Confirmatory Factor Analysis* (CFA) and *Exploratory Factor Analysis* (EFA) [12], [13] where authors of [13] have developed a new two-step approach based on CFA and EFA.

The distinction between CFA and EFA is mainly in the specification and identification steps. In CFA the researcher is sure of the parameters hence he does the estimation and testing to confirm the model while in EFA the researcher may not be sure of the parameters hence he does the testing and subsequently updates the parameters until it narrows down to a closely fitted model. These techniques are well discussed in literature, however, many specialized software like LISREL are being used in academia and industry for model fitting [8], [14]-[16].

The SEM method restricts the modeling around the linear relations between the dependent and independent variables consequently it becomes inadequate to model a non-linear relationship between the dependent (say pressure) and the independent variable (say time). In the literature also the use of fluid dynamics and magneto-hydrodynamics [1], [17], [18] methods have been indicated for modeling the specific cases like Blast-Waves. The models derived by these methods are accurate, but computationally complex and time consuming and moreover this approach may not be practical for real-time simulation of the waves when such simulations are used as inputs for other applications (like sensors). In the present work we have proposed a new model considering the earlier approaches establishing the pressure-time relationship to be non-linear and comprising of exponentially decaying parameters [9] whereas the existing software packages are based on linear model for simplification. The proposed technique uses interactive modeling where the steps of parameter identification and estimation are made feasible through a Graphical User Interface. The user constantly changes the value of parameters and is able to fit the proposed model to the experimental data and verify the result by visualizing the effect and thus the model is narrowed down to close matching as given in sections 2 and 3. Further, the model has been validated using the fundamental techniques like Pearson's correlation and Chi-square goodness of fit test as shown in section 4.

2.2. The universal pressure model

The developed universal pressure-time equation to model the non stationary waves is expressed as:

$$p(t) = k_1[aP_s Cos\{\omega_1(t-t_a)\} + bP_s e^{-d_1(t-t_a)} Sinc\{\omega_2(t-t_a)\} + cP_s Cos\{\omega_3(t-t_a)\} e^{-d_1(t-t_a)}] + k_2 e^{d_2 t} \qquad (2)$$

where a, b, c, ω_1, ω_2, ω_3, d_1 *and* d_2 are constants for a particular type of explosive. t_a is the time of arrival of the peak of shock. P_s is the peak overpressure at a distance. Terms k_1 and k_2 are the modifiers, which describe the pressure phases during explosions. The blast wave generated by high energy (HE) charge and constant volume (CV) gunshot explosion are simulated here using the above model. This estimation, in variance to the traditional SEM techniques, takes into account the non-linear relationship between pressure and time. The natural waves have a tendency to follow the sinusoidal relationships with a damping factor attached due to the presence of viscous medium. This premise helps the authors for basic parameter estimation.

2.2.1. The positive phase of explosion

Considering ideal conditions, the ambient pressure will be the normal atmospheric pressure P_o (0.1

MPa approximately) before explosion and after the disturbance is over. The first term in (2) which is a cosine function, attains the maximum at the time of arrival, decreases thereafter, making the pressure to reach the ambient pressure before entering into the negative phase. The pressure as suggested in (1) decays exponentially; however, the *Sinc*(x) term incorporates rapid fall of the curve. The slopes of the second and third terms in (2) are steeper than that of second term in (1), and are closer to the real model of the blast wave. Also, the interaction of the primary wave with reflected wave is well embodied by '*Sinc(x) or Sin*(x)/x' term in the proposed model.

2.2.2. The negative phase of explosion

The cosine terms in model equation (2) simulates the negative phase of the waveform.

2.2.3. The constant phase of explosion

By "Constant Phase" we mean the quality of certain explosives to exhibit approximately constant amplitude of pressure for certain time (the pressure profile during the gunshot, for example as shown in figure 2). The proposed model embodies all of the pressure phases described above.

3. SIMULATION OF THE MODEL

3.1 Instrument architecture

A dedicated VI, suitable for analysis and synthesis of transient signals, has been designed for two different waves, and entirely realized on a PC using LabVIEW, which uses mathematical model (2) as simulation input. This VI front panel allows complete interactive setting of all acquisition parameters of the subject wave form.

3.2 Simulation result

The "VI panel" was used to simulate the waveform generated by the modeled equation (2) for two cases (CV gunshot and HE charge explosion) where the coefficients were varied iteratively using the VI panel until a close match between the experimental and theoretical waveforms were found (figures 2 and 3). The values of different parameters of the model for matching the simulated wave form with experimental wave form are listed in Table 1. The simulations were done under the assumption of the air surrounding the explosion is still and homogenous, and the explosion source is spherically symmetrical.

Table1. Blast wave parameters for CV gunshot and HE charges.

Parameters	CV Gun Shot	HE charge
a	0.98	0.305
b	0.01	0.545
c	0.01	0.15
w_1	$2.5\text{x}10^{-6}$	$0.63\text{x}10^{-6}$
w_2	0.063	0.063
w_3	0.028	0.028
d_1	8.5	0.755
d_2	4	0
k_1	0 for $t<t_a$ 1 for $t>=t_a$	1
k_2	0.51 for $t<t_a$ 0 for $t>=t_a$	0
P_s	253.8	0.38
t_a	40.11 ms	20ms

The simulation results shown in figures 2 and 3, using the values of constants listed in Table 1, are against one set of experimental data respectively in each of the figures. The results of correlation with different sets of experimental and model generated data are dealt at length in section 4. Therefore using the proposed model and virtual instrument, the pressure versus time curve for different types of explosions can be generated. The waveform parameters are varied using the developed VIs to obtain close match between the experimental and theoretical data.

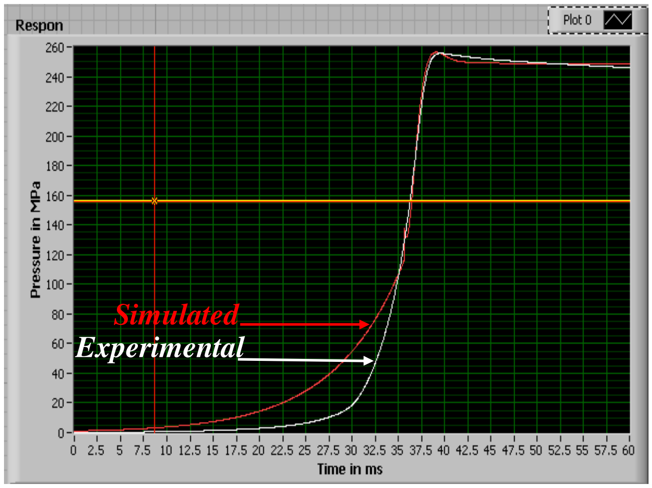

Figure 2. Comparison of simulated *P-T* curve for CV gunshot waveform with experimental data

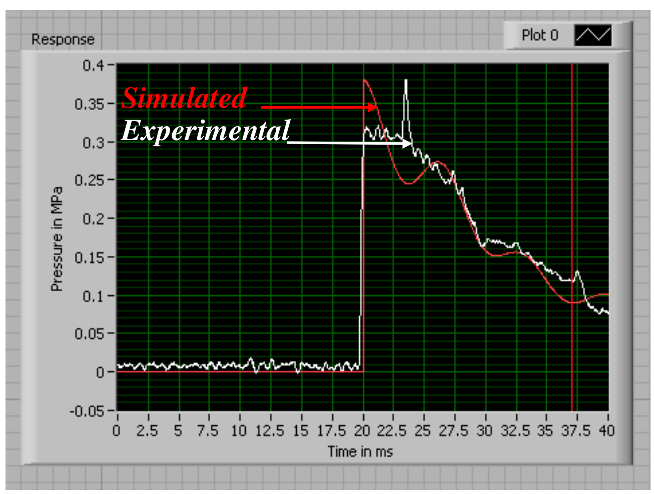

Figure 3. Comparison of simulated *P-T* curve for HE charge explosion with experimental data

4. MODEL VALIDATION

The above simulated results were compared with five sets of data of TNT and gun-shot blasts using Minitab 15 software for (a) Pearson's correlation and (b) Chi-squared goodness of fit test.

Table 2 gives the correlation and p-values between two sets of experimental data of gun-shot blast and one set of the simulated waveform data of the proposed equation (2). The correlation coefficients show a high degree of positive correlation. Also the p-value (<0.05) obtained strongly rejects the null-hypothesis which states that no correlation exists between the simulated and experimental data.

Table 2. Correlation between simulated and experimental waveform of gunshot.

Data-Set	Pearson's Correlation	p-value
Set 1 (Simulated)	0.996	0.000
Set 2 (Experimental)	0.915	0.000
Set 3 (Experimental)	0.994	0.000

Table 3 gives the chi-square goodness of fit test result between the experimental data of gun-shot blast and the simulated waveform of the proposed equation (2). The data set used here is the same as that used in figure 2 (the data set 1 in Table 2). Also, the obtained p-value (> 0.05) strongly accepts the null-hypothesis which establishes that the proposed model fits with the experimental data. Similarly the parameter values (Table 1) can be altered by the GUI to fit the other experimental data sets.

Table 3. Chi-square test result between simulated and experimental waveform of gunshot.

N	DF	Chi-sq (χ^2)	p-value
200663	841	46.6036	1.000

Table 4 gives the correlation and p-values between experimental data of HE-charge blast and the simulated waveform of the proposed equation (2). The correlation coefficients show a high degree of positive correlation. Also, the obtained p-value (<0.05) strongly rejects the null-hypothesis which states that no correlation exists between the simulated and experimental data.

Table 4. Correlation between simulated and experimental waveform of HE-charge.

Data-Set	Pearson's Correlation	p-value
Set 1 (Simulated)	0.750	0.000
Set 2 (Experimental)	0.961	0.000

Table 5 gives the chi-square goodness of fit test result between the experimental data of HE-charge blast and the simulated waveform of the proposed equation (2). The data set used here is same as shown in figure 3 (the data set 1 in Table 4). Also, the obtained p-value (> 0.05) strongly accepts the null-hypothesis which states that the proposed model fits with the experimental data. Similarly the parameter values (Table 1) can be altered by the GUI to fit the data set 2.

Table 5. Correlation between HE-charge simulated and experimental waveform.

N	DF	Chi-sq (χ^2)	p-value
142.956	1500	13.4754	1.000

Further, it is obvious from above tables and figures 2 and 3 that the simulation results show a close matching with the experimental results, even in a better way when compared to one of the reported case [11] and thus, validates the proposed model of the pressure wave.

5. CONCLUSION

In the present work a mathematical formulation has been proposed for (blast) pressure waves and its simulation through Virtual Instrument has been implemented. This model calculates the pressure profile experienced as a result of the detonation of high explosives. It relies on the use of pre-computed blast curves to calculate all the parameters necessary.

Our modelling approach strikes a good balance between accuracy and computational complexity. It provides a marked improvement over earlier methods. Although a general claim for high accuracy in prediction of blast pressure cannot be made due to unavailability of extensive experimental explosion data due to being of classified nature, however, promising results for the limited number of tested cases were obtained. The simulated and experimental wave forms are found to be in close matching which has been proved by obtaining a close fit for one set of experimental data by varying the parameters and then comparing the result with other sets of experimental data obtained under similar conditions. Thus, the solution proposed in this work is a simple technique leading to accurate pressure - time modelling of blast wave in homogenous media.

The generic nature of the proposed equation indicates that with few minor modifications, it can be extended to other types of explosives (like fuel-air explosives) and other natural high-pressure phenomenon as well.

Our blast wave model leaves room for extensions and improvements, which would allow the simulation of more complex wave interactions with the environment. Possible refinements include modelling the compression of air in front of impacted objects and incorporating the effect of reflections. This work is potentially useful for the *design of pressure sensors, accelerometers* and *explosives* etc.

References

[1] B. Vanderstraeten, M. Lefebvre, J. Berghmans, (1996) “A Simple Blast Wave model for bursting spheres based on numerical simulations”, *Journal of Hazardous materials*, vol. 46, pp. 145-157.

[2] Souichi Murata, (2006) “New Exact Solution of the Blast Wave problem in gas dynamics”, *Chaos, Solitons and Fractals,* vol. 28, pp. 327-330.

[3] H.L. Brode, (1995) “Numerical Solutions of Spherical Blast Waves”, Jour. *Appl. Phys.*, vol. 26, pp. 766-775.

[4] B. Vanderstraetena, M. Lefebvreb, J. Berghmansa (1996), “A simple blast wave model for bursting spheres based on numerical simulation”, *Journal of Hazardous Materials*, vol. 46, pp. 145-157.

[5] Michael Neff, (1998) “A Visual Model for Blast Waves and Fracture”, *Master's Thesis, Department of Computer Science, University of Toronto*. [Online]. Available:http://www.dgp.toronto.edu/~neff/BlastThesis.ps.gz.

[6] G. Bucci, A. Germano, and C. Landi, (1996) “The Real-Time Implementation of a Model-Based Measurement Technique on a Multiprocessor Instrument”, IEEE *Transactions on Instrumentation and Measurement,* Vol. 45, No. 1, pp. 238-243.

[7] K. Konstantinides, and J. R. Rasure, (1994) “The Khoros Software Development Environment for Image and Signal Processing”, *IEEE Transactions on Image Processing,* Vol. 3, No. 3, pp. 243-252.

[8] R. E. Schumacker and R.G, Lomax, (2004) “A beginner's guide to structural equation modelling”, *LEA Publishers*, New Jersey.

[9] Oleg Mazarak, Claud Martins, and John Amanatides, “Animating Exploding Objects”, *Department of Computer Science, York University*. [Online]. Available: http://www.cse.yorku.ca/~amana/research/explosion.pdf

[10] W.E. Baker, (1973) “Explosions in Air”, *University of Texas Press*, Austin.

[11] Kristina Ahlin, (2000) “Modeling of pressure waves in the Common Rail Diesel Injection System”, Master's Thesis, Department of Electrical Engineering, Linkoping University, Sweden.

[12] J. B. Ullman, (2006) “Structural Equation Modeling: Reviewing the Basics and Moving Forward in Statistical development and applications”, *Journal of Personality Assessment,* vol. 87(1), pp. 35-50.

[13] J. C.anderson and D. W. Gerbing, (1988) “Structural Equation Modeling in Practice: A Review and Recommended Two-Step Approach”, *Psychological Bulletin,* vol.103, No.3, pp. 411-423.

[14] B. Muthen and M. Hollis, (1987) “On Structural Equation Modeling with Data that are not Missing Completely at Random”, *Psychometrika,* vol.52 (3), pp. 431-462,.

[15] John Fox, (2006) “Structural Equation Modeling with the SEM Package in R”, *Structural Equation Modeling,* vol. 13(3), pp. 465- 486.

[16] R. P. Bagozzi and Y. Yi, (1988) “On the Evaluation of Structural Equation Models”, *Journal of the Academy of Marketing Science*, spring, vol. 16, No.1, pp. 074-094.

[17] Summers D., (1975) "An idealized model of a magneto hydrodynamic spherical blast wave applied to a flare produced shock in the solar wind", *Journal of Astronomy and Astrophysics,* vol. 45, no. 1, pp. 151-158.

[18] D. P. Cox and P. R. Anderson, (1982) "Extended Adiabatic Blast Waves and A Model of the Soft X-Ray Background", *The Astrophysical Journal,* vol.253, pp. 268-289.

Authors

B. S. Chaurasia obtained B. Tech. and Ph.D. degrees respectively in Electronics Engineering in the years 1983 and 2010 from Dept. of Electronics Eng., Institute of Technology, Banaras Hindu University (BHU), Varanasi, India. He has appreciable Industrial experience and Patents in his name. His research interest includes micro Sensors, high pressure measurements, microelectronics, VLSI techniques etc..

S. Tandon obtained B.Tech Degree in Electronics Engineering from Dept. of Electronics Eng., Institute of Technology, Banaras Hindu University (BHU) in 2006. Presently he is working as ASIC Design Engineer, nVIDIA Graphics Pvt Ltd., Bangalore, India.

S. Shukla completed B. Tech. in Electrical Engineering in 2008 from Institute of Technology, BHU, Varanasi.

P. Mishra completed B. Tech. in Electrical Engineering in 2008 from Institute of Technology, BHU, Varanasi.

Anand Mohan obtained B.Sc. in Electronics Engineering, M.Tech. (Electronics) and Ph.D. from Banaras Hindu University (BHU), Varanasi, India in 1973, 1977 and 1994, respectively. During December 1975 to March 1979 he worked as R&D Engineer in Murphy India Ltd. Maharashtra, India. He was Head of Department of Electronics Engineering, Institute of Technology, BHU. Currently he is Professor and Coordinator of Centre for Research in Microprocessor Applications, Electronics Engineering, Institute of Technology, BHU. He has authored and coauthored 62 research papers in International/National Journals, Supervised/Co-supervised four Ph.D. thesis and 35 M.Tech. Dissertations. His co-authored papers have been received awards of International Union of Radio Science (URSI), Belgium-2005, Institution of Engineer (India) – 2003–04 and Indian Science Congress Award–1999. His area of current research in thrust is Programmable Logic Devices, Fault Tolerant Design and Digital Steganography. He has been reviewer for IEEE Transactions on Computers, Tata McGrawhill and Indian Society for Technical Education (ISTE) Learning Materials. He is Fellow of Institution of Electronics and Telecommunication Engineers (IETE), Institution of Engineers (India) and Life Member of Indian Society for Technical Education (ISTE).

***S. K. Balasubramanian* was** born on 1st May 1950. He did his Bachelor's degree in 1972 in Electronics and Communication Engineering from College of Engineering, Madras (presently Anna University, Chennai), his Master's degree in 1975 in Solid State Electronics from the University of Roorkee (presently IIT-Roorkee) and his Doctoral degree in Electronics Engineering from Banaras Hindu University. He worked as a faculty member in Regional Engineering College, Tiruchirapalli for a short period before joining the University of Roorkee for his post graduation. After his post graduation he joined the Department of Electronics Engineering, Institute of Technology, Banaras Hindu University in 1975 and presently working as a professor. His areas of interest are semiconductor devices and circuits, microelectronics and VLSI. He has taught many subjects — to name a few are Microelectronics, IC Technology, VLSI Design and Electronic Devices and Circuits. He was pioneer in the development of thin-film, thick-film, IC fabrication, VLSI and Software laboratories in the department. He is the Coordinator of the project "Special Manpower Development on VLSI and Related Software" sponsored by the Department of Information Technology, Ministry of Communication and Information Technology and Principal Investigator for a project on "Simulation Studies of Polycrystalline Pressure Sensors" sponsored by ARMREB, DRDO.