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Deep Learning-Based Reduced-Order Methods for Fast Transient Dynamics

Martina Cracco[1], Giovanni Stabile[1,3], Andrea Lario[1], Armin Sheidani[1,4], Martin Larcher[2], Folco Casadei[2], Georgios Valsamos[2] and Gianluigi Rozza[1,*]

[1] *SISSA, International School for Advanced Studies, Mathematics Area, mathLab, via Bonomea 265, 34136 Trieste, Italy.*
[2] *European Commission, Joint Research Centre, Via Enrico Fermi 2749, 21027 Ispra (VA), Italy.*
[3] *The Biorobotics Institute, Sant'Anna School of Advanced Studies, V.le R. Piaggio 34, 56025, Pontedera, Pisa, Italy.*
[4] *Fluids and Flows group, Department of Applied Physics and Science Education, Eindhoven University of Technology, Eindhoven, P.O. Box 513, 5600 MB, The Netherlands.*

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Abstract. In recent years, large-scale numerical simulations played an essential role in estimating the effects of explosion events in urban environments, for the purpose of ensuring the security and safety of cities. Such simulations are computationally expensive and, often, the time taken for one single computation is large and does not permit parametric studies. The aim of this work is therefore to facilitate real-time and multi-query calculations by employing a non-intrusive Reduced Order Method (ROM).

We propose a deep learning-based (DL) ROM scheme able to deal with fast transient dynamics. In the case of blast waves, the parametrised PDEs are time-dependent and non-linear. For such problems, the Proper Orthogonal Decomposition (POD), which relies on a linear superposition of modes, cannot approximate the solutions efficiently. The piecewise POD-DL scheme developed here is a local ROM based on time-domain partitioning and a first dimensionality reduction obtained through the POD. Autoencoders are used as a second and non-linear dimensionality reduction. The latent space obtained is then reconstructed from the time and parameter space through deep forward neural networks. The proposed scheme is applied to an example consisting of a blast wave propagating in air and impacting on the outside of a building. The efficiency of the deep learning-based ROM in approximating the time-dependent pressure field is shown.

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*Corresponding author. *Email address:* `grozza@sissa.it`

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1 Introduction

Blast waves in cities can be caused by a terrorist attack or an accidental explosion and can provoke human casualties, different types of injuries and damage on buildings and other infrastructure. Due to the emerging threat for urban environments concerning terrorist attacks in the last decades, computational simulations have been increasingly used to identify vulnerabilities and propose protective solutions for modern cities. Recent investigations include the design of access control points (Larcher *et al.* [27]), the risk assessment in a transport infrastructure (Valsamos *et al.* [41]) and the large-scale simulation of the explosion occurred in the port of Beirut in 2020 (Valsamos *et al.* [42]).

For explosions in an urban environment, one has to distinguish between the direct effects if the explosive is attached or close to a structure whose material is heavily damaged by the blast and the far-field effects of the so-called blast wave that is the focus of this work. Typically a free blast wave propagates spherically from the source of the explosion. Its pressure characteristic can be calculated in the purely spherical (or hemispherical) case by several empirical equations (Karlos *et al.*. [23]). In general, it can be said that the pressure wave is decreasing by a cubic root with the distance. But the spherical propagation might be greatly altered by reflections, shadowing and chanelling. A pressure wave hitting a rigid structure is reflected and its pressure intensity is increased by a substantial amount. Similarly, structures can shadow the area behind them since the pressure waves cannot reach these areas directly. In that case, the pressure might be much smaller and might also not be critical anymore. In the case of explosions in tube- or channel-like environments, the decrease of the pressure wave due to spherical propagation does not occur and the pressure wave amplitude might remain similar also at much bigger distances. The effects of such blast waves in the far-field concern mainly the consequences on humans (Solomos *et al.* [36]) and the loading of lightweight structures, in particular windows. The use of laminated glass (Larcher *et al.* [26]) can reduce the risk of humans inside the buildings dramatically. Standards for testing such kind of structures under different blast loading are available and currently under review (Larcher *et al.* [24]).

In industrial applications, many problems require dealing with real-time or multi-query scenarios. In the case of blast waves in urban environments caused by an explosion, being able to perform parametric studies and estimate the damage to buildings and the risk to humans in real time is crucial. For instance, in the disaster intervention units, it is necessary to understand the damage level on critical infrastructures after a blast event and adapt the intervention emergency strategy accordingly. Since these sorts of problems are to be solved in a usually very large domain (an entire city in some specific cases), they