Effect of local mass distribution on modal behavior of Aluminum foam

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Abstract— Free vibration analysis of aluminum foam sample is performed in the present paper. Mechanical properties of metallic foams depend on their relative densities. The discrete mass distribution of metallic foam causes discontinuities in their local properties. X-ray computer tomography (XCT) revealed the 3-D inhomogeneous mass distribution in metallic foams. The density mapping method is used to approximate the aluminum foam trade name ALPORAS by a continuous, 3-D density distribution at the mesolevel. The density recorded by XCT is homogenized over an averaging volume. A continuum model is implemented using the finite element (FE) method to simulate the effect of local mass distribution on the modal behavior of metallic foam sample. The effect of measured density distributed model (MDDM) Coarse sub-domain density model (CSDM), uniform average density model (UADM), and three random distributed density model (RDDM) on eigen frequencies of the aluminum foam sample is studied. Density distribution of aluminum foam measured by X-ray computer tomography was used as input to the corresponding FE model of investigated specimen. All numerical investigations were carried out by means of the FE package ANSYS.

Index Terms— Vibration analysis, X-ray computer Tomography, Finite element modeling, Alporas, Inhomogeneous mass distribution, Aluminum foam.

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1 INTRODUCTION

Porous metals, metallic foams and cellular materials are materials with pores deliberately integrated in their structure. Porous metals refer to the metals with a large volume fraction of porosity, whereas the term foamed metal or metallic foams applies to porous metals fabricated through the foaming process [1]. Mechanical properties of metallic foam structure depend on the relative density of the structure. Relative density is the density of the foam material divide by that of the solid from which the cell walls are made. This influence, imperfectly understood at present, is a topic of intense study. Various constitutive relations have been suggested for the characterization and modeling of this relationship [2].

Gibson and Ashby [3], Zhu [4] and Ko [5] et. al proposed different approaches based on a regular cell. They assume scaling laws to link the elastic moduli, the elastic collapse stress and the plastic collapse stress of the cellular material to the elastic modulus and the yield stress of the solid material and to the relative density of the foam. The relative density is the only parameter available for the description of the microstructure [6]. Some approaches assume that the structure can be represented by a strut pattern that is either regular [7-8] or irregular [8-9]. The structures described in this way are more regular than the ones observed in reality. These models are also most of the time devoted to small density cellular materials. Another improvement in the mechanical description of the problem has been proposed by Roberts and Garboczi [10]. These authors use a voxel description of the solid volume as an input for the generation of a Finite Element (FE) model of the material. This approach enables the complete description of the actual structure, numerically generated [10] or obtained by means of X-ray tomography images [11].

Several constitutive material laws describing the overall behavior of cellular metals have been proposed and applied in the simulation of components consisting of or containing metallic foams. Obviously, the selection of a particular material law is governed by the required material parameters and by the effort necessary for calibrating them by experiments or via micromechanical studies. Because they are based on the use of an equivalent homogeneous continuum, macroscopic material laws should only be used for studying components or samples that are considerably larger and thicker than the typical cell size of the foam.

The most basic aspect of the mechanical material characteristics of inhomogeneous material is their linear elastic behavior, which can be describe in term of overall elasticity tensor or appropriate effective moduli. Linear dependence of plateau stress, Young's modulus and energy absorption capacity with relative density is reported in [12-14]. Aluminum foam is one of the common metallic foam, many researcher have investigated the mechanical properties of various aluminum foams e.g. Alporas [15-16] and Alulight [17]. All the results show that Young's modulus and yield stress are related to the relative density. The general equation for the plateau stress of regular hexagonal closed-cell foam is suggested by Gibson and Ashby [3] and is given by;

$$\frac{\sigma^*_{\mathrm{pl}}}{\sigma_{\mathrm{ys}}} = 0.3\emptyset^{3/2}\left(\frac{\rho^*}{\rho_{\mathrm{s}}}\right)^{3/2} + (1-\emptyset)\,\frac{\rho^*}{\rho_{\mathrm{s}}} \tag{1}$$

The equation for the theoretical elastic modulus of a closed-cell foam is expressed as [3];

$$\frac{\mathrm{E}^*}{\mathrm{E}_{\mathrm{s}}} = \emptyset^2\left(\frac{\rho^*}{\rho_{\mathrm{s}}}\right)^2 + (1-\emptyset)\,\frac{\rho^*}{\rho_{\mathrm{s}}} \tag{2}$$

Where $\emptyset$ (Phi) is the volume fraction of solid contained in the cell edges, the remaining fraction $(1-\emptyset)$ is in the cell faces. E^*, σ^*_{pl}, ρ^* are the Young's modulus, yield stress and density of metallic foam and E_{s}, σ_{ys}, ρ_{s} of matrix material respectively.

Lou et al. [18] investigated effects of local damage on the natural frequencies and the corresponding vibration modes of composite pyramidal truss core sandwich structures. They observed that the structural natural frequencies decrease due to the loss of stiffness caused by the existence of local damage of the truss core.

The objective of the current paper is to analyze the local mass effect on modal properties of aluminum foam. For this purpose two aluminum foam structure with different densities are selected. Experimental modal testing in free-free condition was performed using laser scanning vibrometer. A continuum model was implemented using the finite element (FE) method to simulate the effect of local mass distribution on the modal behavior of metallic foam sample.

2. EXPERIMENTAL

2.1. Materials

The test material used in the present study is an alloy supplied by Shinko wire, with the trade name ALPORAS [1]. Alporas foams were supplied as large plate, 2000 × 400 × 30 mm3, without skin on the outer surface which cut into smaller panels. Two aluminum foam specimen are investigated. The Alporas_B2 has low density as compared to Alporas_B3. Dimensions, relative densities and the density mapping mesh measured by CT are summarized in Table 1.

Table 1 Specification of aluminum foam specimen

Material	Size (cm³)	Average density (g/cm³)	Density mesh measured by CT
Alporas_B2	49.6×40×3.02	0.247	55×40×5
Alporas_B3	49.7×40×3.09	0.466	55×40×5

2.2. Experimental modal testing

Experimental setup for extracting the modal response of aluminum foam structure has been developed [19]. The main purpose of developed setup is to measure eigen frequencies and mode shapes of aluminum foam sample, as precisely as possible and noninvasive. The equipment involved in this set-up consist of a laser scanning vibrometer; Polytec PSV-300-F, a controlled pseudo-random noise signal generator, A mini excitation shaker, power amplifiers and a vibration isolated table to prevent surrounding vibration. Free-free boundary conditions are chosen for the tested specimen, in order to improve the correlation between the experimental tests and the numerical results derived from the finite element model. Modal analysis of aluminum foam specimens are conducted on a range of frequency from 10 Hz to 3 kHz. The spectral lines measured are set to 3200 lines and an average of 30 measurements per point is made to increase the signal-noise ratio. Data acquired by PSV scanning vibrometer is imported in LMS Test. Lab using the Polytec data driver add-in. Modal analysis is performed on the acquired data and modal parameters are extracted using LMS PolyMAX method [20]. The experimental modal testing setup is shown in Fig. 1.

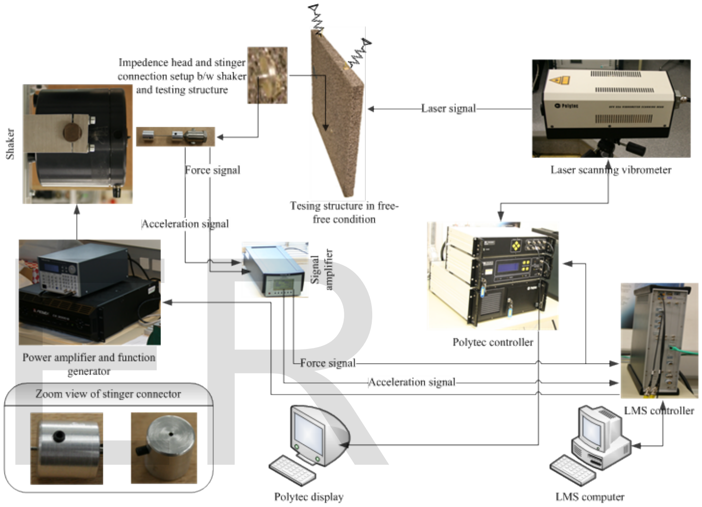

Fig 1 Experimental configuration [17]

2.3. Finite element modelling

A special procedure called density mapping method is applied to approximate the cellular structure of aluminum foam with continuum. The microscopical density distributions of the AF, recorded by X-ray computed tomography are averaged over a certain domain. The local average density represented by a mean density forms a so called 'sub-domain'. All finite elements in the sub-domain behave mechanically in the same way. Each sub-domain is assumed to be homogeneous and isotropic. Density distributions of AF measured by X-ray computer tomography are used as input to the corresponding FE model of investigated specimen. Its mechanical properties are modeled using Gibson and Ashby scaling law (2) for regular foams. In this scaling law, the microstructure of cellular materials is homogenized over a scale infinitely larger than the typical microstructure. In other words these relations predict the behavior of a material that is assumed to be a homogeneous continuum. The input mechanical properties of the bulk material used in scaling law (2) for AF specimens are Young's modulus of 69 GPa and density of 2700 Kg/m3. Complex modal analysis is performed using QR Damped method. This method is faster and more stable than the existing damped solver. It combines the best features of the real eigensolution method (Block Lanczos) and the Complex Hessenberg method (QR Algorithm). Outputs are complex eigenvalues (frequency and stability) and damping ratio of each mode.

All numerical investigations are carried out by means of the FE package ANSYS that defines the preprocessor (parametric model of the AF specimen), solution and postprocessor phase of the finite element analysis. In the preprocessor phase, the geometry and the boundary conditions of the model are defined using a set of APDL commands. QR damped method is used in solution phase to solve the model, build in preprocessor phase. In the postprocessor phase the results from the analysis was gathered and saved in a suitable format (file) for further use.

3. RESULTS

3.1. X-ray tomography:

The measured density distribution of Alporas_B2 and Alporas_B3 is shown in Fig. 2 and Fig. 3 respectively. This density mapping is measured by computer tomography and the calculated values of sub-domains are saved in an array of size 55×40×5 in x, y and z direction respectively. The density distribution shown in Fig. 2 and Fig. 3 is the average distribution in z direction. It can be observed that Alporas_B2 and Alporas_B3 specimen is roughly divided in to three and five areas respectively, based on the average density values. Looking at Fig. 3 and starting from the top edge, the first uniform density area (UDA) is with blue color than second thin UDA with aqua and third UDA comparatively wide, with android green having some sub-domains with yellow color, fourth UDA again with aqua color and fifth UDA with blue color having yellow and red color sub-domains. The color bar is also shown along Fig. 3.

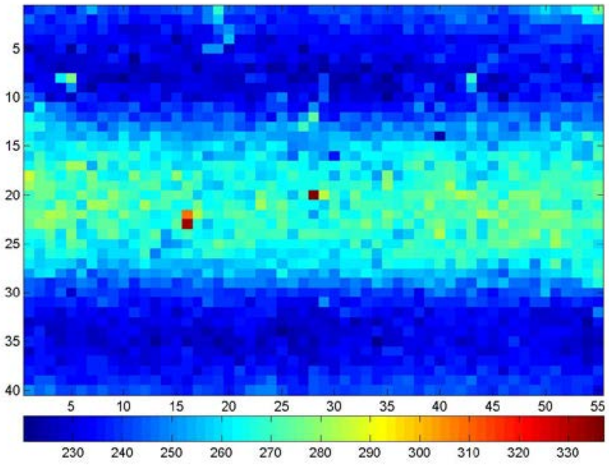

Fig 2 Density distribution of Alporas_B2

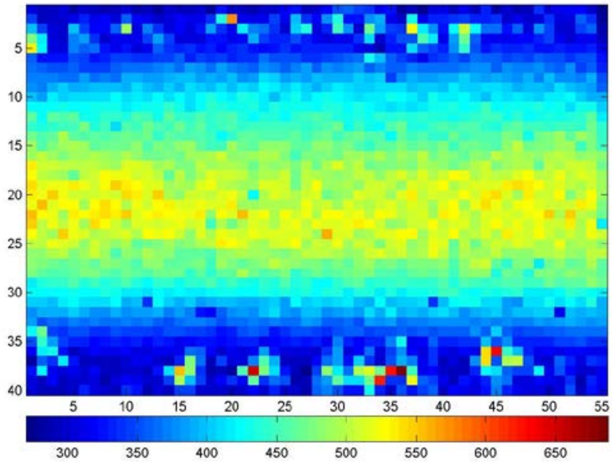

Fig 3 Density distribution of Alporas_B3

3.2. Modal analysis

The average spectrum of measured transfer functions of test specimen Alporas_B2 and Alporas_B3 is shown in Fig 4 (a) and Fig 4 (b) respectively. Measured transfer function quality is excellent with a large number of close peaks, thus providing the effectiveness of the laser scanning (non contact) measurement method. Very strong mutual influence of some resonance peaks is evident here and the LMS PolyMAX extraction procedure is essential to accurately determine the close eigen frequencies and mode shapes. On average, 18-20 modes are extraxted in a frequency range of 10 Hz to 3 kHz. The quality of measurements are verified, FRF's are saved in a UNV file format and are imported in LMS Test.Lab. The LMS PolyMAX method is used to estimate the modal parameters precisely.

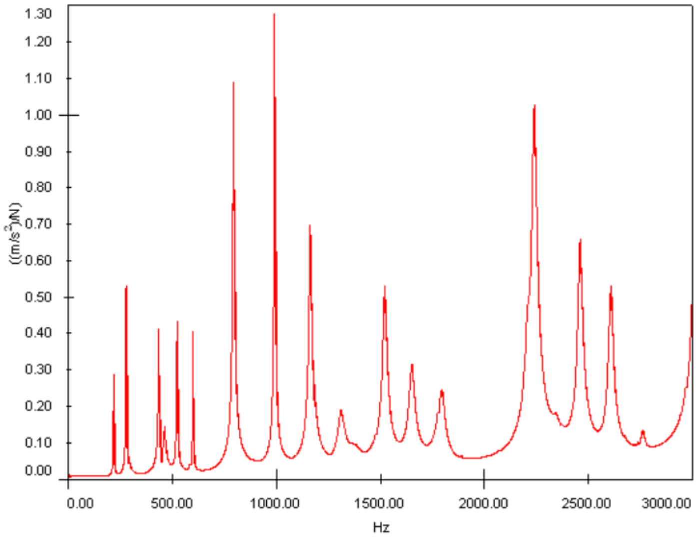

Fig 4(a) Average measured frequency response function of testing specimen Alporas_B2

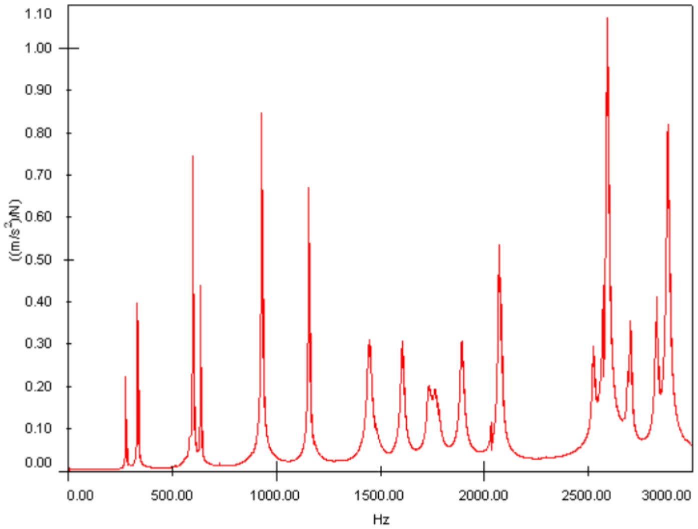

Fig 4(b) Average measured frequency response function of testing specimen Alporas_B3

3.3. FE modeling

The density mapping is measured by computer tomography and the values are saved in an array of size 55×40×5 in x, y and z direction respectively. Numerical investigations are performed to analyse the behavior of aluminum foam due to variable density distribution. In first case a coarse sub-domain density model (CSDM) is used. Array of size 11×8×1 in x, y and z respectively, in which each component is average of 5 components in each direction (average of total 125 components as MDDM is of size 55×40×5) is assigned to CSDM. In second case a uniform average density model (UADM) is used in which density assigned is a single uniform value. In 3rd, 4th and 5th cases random distributed density model (RDDM) is used. In these cases different random distributions of measured density are assigned to the FE models.

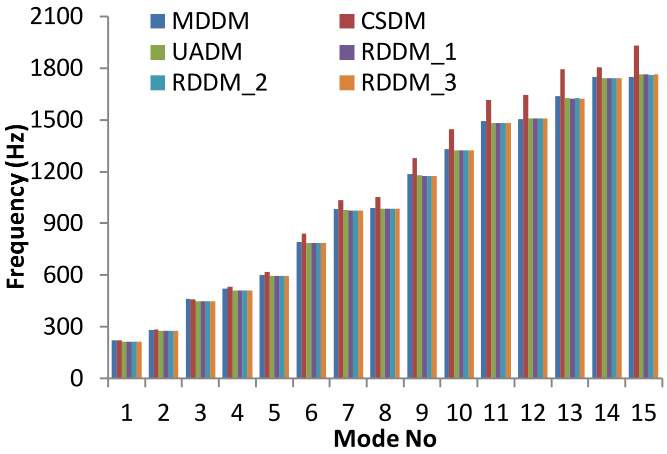

Fig 5(a) Frequencies (Hz) predicted from FE models based on densities distribution mapping of Alporas_B2

Numerical modal analysis is performed for all cases, the eigen frequencies of Alporas_B2 and Alporas_B3 as a results of modal analysis solution for all cases are shown in Fig.5 (a) and Fig.5 (b) respectively. The eigen frequency of corresponding mode shapes of Alporas _B3 are higher than Alporas_B2 obviously due to high density of the specimen.

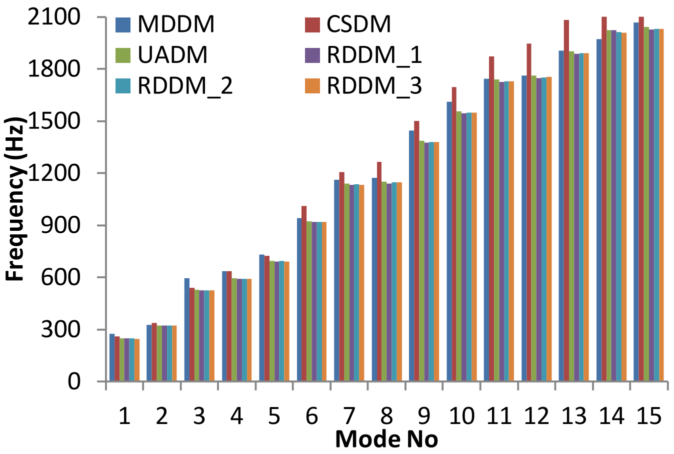

Fig 5(b) Frequencies (Hz) predicted from FE models based on densities distribution mapping of Alporas_B3

4. DISCUSSION

Experimental setup is developed to evaluate modal parameters, precisely. To achieve precision, an experimental setup of non contact vibration measurement using scanning laser vibrometer is used. The transfer functions of the test specimen, velocity/force type was calculated by the internal software system PSV200 and an average of several measurements was performed to further increase the quality of the experimental frequency model. The FRFs from PSV200 were imported in LMS Test.Lab. The state of the art LMS PolyMAX parameter estimation technique was used to determine the eigen frequencies in range of 10 Hz to 3 KHz.

The second specific task of this research was to develop an FE model of AF material based both on the cellular microstructure and behavior of the bulk material. Computational modelling and simulation of materials with a cellular microstructure is a broad field of research that has drawn considerable interest for engineers. Computed tomography as a non-destructive testing method has the potential to study the internal configuration of the structure, in which density changes over a sufficient volume. Aluminum foams are composite consisting of metal and air can fulfill this condition very well. These metals can be analyzed in two ways; (i) reconstruction of the microstructure to analyze the 3D distribution of solid (ii) transformation of heterogeneous microstructure to an approximated continuum. To reconstruct the microstructure high resolution CT-data is required. Only micro-CT can provide this high resolution data, required for this purpose. Then a FE model of this reconstructed microstructure can be generated as described in [2, 21]. Such a model would have a high number of elements which makes the model too complex to easily handle in FE packages and computing time would be high as well. One of the most important feature of a cellular solid is its relative density; ρ^*/ρ_s where ρ^* is the density of the cellular material and ρ_s is the density of the solid from which the cell walls are made.

Numerical investigations were performed to observe the behavior of aluminum foam due to the variable density distribution. In first case a coarse sub-domain (which is 5 times greater in each direction than the previously modeled) was used in the FE model. The density assigned to elements in each subdomain was the average density of that sub-domain. In second case a uniform average density was assigned to the whole FE model instead of measured one. In 3rd, 4th and 5th cases different random distribution of measured density was assigned to the FE model. MATLAB routines were developed to do these tasks of different density distributions. Numerical modal analysis was performed for all cases with the identified variable parameters from MDDM. It was observed that the corresponding eigen frequencies of the models with uniform and random density distribution are lower than the MDDM. Similarly in case of coarse sub-domain model the first torsional and bending (Alporas_B2 and Alporas_B3 in y-axis while in case of Alporas_S2 and Alporas_S3 in x-axis) mode have lower while other modes have higher corresponding eigen frequencies than MDDM. The corresponding eigen frequencies difference among the RDDM's is very minor but UADM has slightly higher corresponding values than RDDM's. These observations show that density distribution should not be ignored in FE modeling of these cellular materials. It was therefore concluded from these investigations that FE modeling of specimen and non contact measurements method for modal analysis extend the scope of mixed numerical experimental technique.

5. CONCLUSIONS

Dynamic behavior of closed cell material ALPORAS was investigated experimentally and numerically. Following conclusions can be drawn from the present research

- In the context of materials engineering, the present approach can be very useful for designing cellular materials. The present approach enables the prediction of the best way of combining the mechanical properties of the solid material with feasible microstructures, in order to obtain expected mechanical properties.
- Experimental results of modal testing show high scatter in the modal properties of investigated specimens. This phenomenon can be well described by the effect of inhomogeneous mass distribution.
- The computed behavior of the foam was very sensitive to these input parameters. The model can be adjusted by introducing a correction on the mechanical properties parameters of the bulky material.

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