PAPER ID: 0395
DOI: 10.18462/iir.compr.2021.0395

COMPRESSOR MUFFLER DESIGN CONSIDERING FLUID-STRUCTURE INTERACTION

Paulo Martins[(a)], Rafael Veloso[(a)], Eric Murakami[(a)]

[(a)] Secop Austria GmbH
Fürstenfeld, 8280, Austria, paulo.martins@secop.com, rafael.veloso@secop.com, eric.murakami@secop.com

ABSTRACT

This paper investigates the importance of considering fluid-structure interaction (FSI) while designing new suction/discharge mufflers made of polymeric material. This necessity arose from experimental results deviating from simulations of such components, considering only standard transmission loss simulations with rigid walls. For that reason, we simulated new FE models with ANSYS software and ACT add-on, with and without FSI, to evaluate the relevance of their differences. Furthermore, the results from new FE models were correlated with experiments to assess its significance. Finally, a heuristic optimization process was carried, and different designs of mufflers were simulated, prototyped and tested under working conditions. The results, originated from the optimization, are discussed.

Keywords: Acoustics, Muffler, Design, FSI, FEM, Optimization

1. INTRODUCTION

Mufflers design with fluid-structure interaction (FSI) is not a widely discussed topic on the literature, since it is mostly applied in auto industry, as means of reducing the noise from combustion engines. Such applications require mufflers made of metallic alloys, which can withstand high temperatures and pressures. In this case, acoustic models of mufflers, considering rigid walls, can accurately predict their behavior.

On the other hand, mufflers made of polymeric materials are commonly used for refrigeration application and compressors, due to their low-cost, easiness of production and performance. A typic rotary compressor uses a crank system, powered by an electric motor, enclosed by a hermetic housing, which pumps a refrigerant gas into a closed-loop system. The cyclic pumping of refrigerant gas generates enough pressure oscillation, which needs to be controlled to avoid undesirable effects, such as exciting the acoustic modes of the enclosed fluid (cavity). However, the muffler's vibratory characteristics and the cavity's acoustic characteristics can be quite similar, which leads to a significant fluid-structure interaction.

We could observe from experimental data that rigid wall simulations did not accurately represented the reality. More specifically, we designed and prototyped a muffler to filter a specific frequency band, but results were inconclusive and will be discussed in the following sections.

Therefore, this work was organized as follows: A brief literature review, with works that addresses similar problems with fluid-structure interaction. Then, the definition of the problem and methodology used to mitigate. Finally, results and discussion will be presented, followed by suggestions for future works.

2. LITERATURE REVIEW

(Corral, Floody, & Venegas, 2016) found a strong variation while considering flexible walls, so they applied genetic algorithms on transfer matrix and FE models to optimize the shape of mufflers. Their methodology and results were remarkably related to ours, thus we often referred to it for comparison purposes. In addition, (Xu, Zhang, Ge, & Liu, 2019) observed the same variation in the muffler performance due to fluid-structure coupling.

DOI: 10.18462/iir.compr.2021.0395

Therefore, they used a similar approach to optimize the muffler with FE discretization and modal superposition. They achieved a more realistic transmission loss, considering flexible walls. They also have identified that an average transmission loss under acoustic-structure coupling decreased by 7.4%.

(Choi, Dong, Vlahopoulos, Wang, & Zhang, 2003) proposed a model based on the Energy Finite Element Method (EFEM), to predict the structural-acoustic responses in high frequency range. They modeled the structure-fluid coupling using radiation efficiency, and presented a design sensitivity analysis of panel thickness and material damping. Although their work has a different proposal from the present paper, the results about panel thickness sensitivity gave an important insight on our issue.

Furthermore, (Soize & Michelucci, 2000) developed a method of solving a structural shape optimization problem, considering a flexible wall. Despite their work focuses on a different aspect of fluid-structure interaction, it gave a good estimate on how sensitive a system can be when the parameters have a similar magnitude of the ones currently analyzed.

3. PROBLEM DEFINITION AND METHODOLOGY

Our object of study is a typical compressor for light commercial applications, which showed a high level of noise coming from 2000 Hz, 2500 Hz and 3150 Hz one-third octave bands. This can be observed in Figure 1, which shows a normalized sound power level spectrum from the stock sample, assembled with a standard suction muffler, measured at CECOMAF standard conditions of low back pressure (LBP) and medium back pressure (MBP). The LBP consists in fixing -25°C on the evaporator side and 45°C at the condenser side, while the MBP consists in -10°C on the evaporator and 45°C on condenser. Also, the compressor was measured after its shell temperature had stabilized in 50°C. We used R290 as refrigerant gas and the device was running at 3000 RPM.

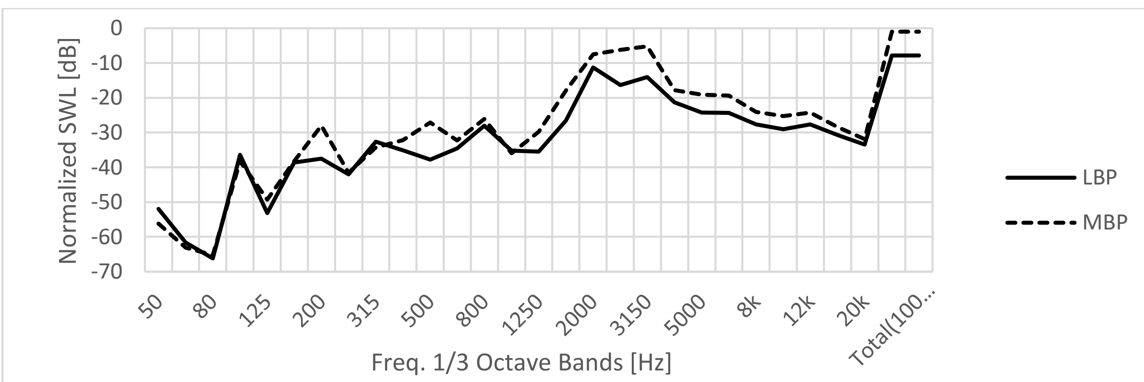


Figure 1. Normalized sound power level spectrum from the sample at CECOMAF conditions of low back pressure (LBP) and medium back pressure (MBP).

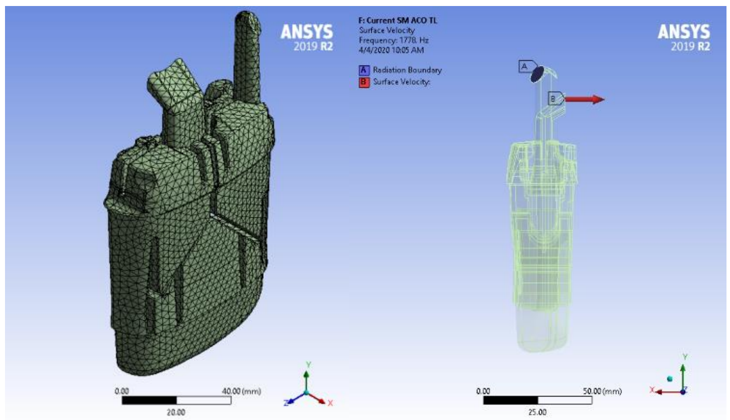
After thorough investigation, we were able to pin-point the 2000 Hz band problem on an interaction between suction pulsation and acoustic cavity. Therefore, we focused the research into the muffler optimization on the suction side. The aim was to reduce the suction pulsation created by the suction valve while respecting some boundaries, such as size limitation and producibility.

The suction muffler had a first pipe length of approximately 91 mm, connected to the first volume of approximately 52500 mm³, which is connected to the second volume by 2 small passages. This second volume have approximately 65900 mm³, which is connected to the outlet by another pipe, of roughly 49 mm. Also, the structural part of this suction muffler had an average thickness of 2.3 mm.

DOI: 10.18462/iir.compr.2021.0395

Thus, we modeled the suction muffler with the FE method using ANSYS software, version 2019 R2 and ACT add-on. This preliminary model considered rigid muffler walls, maximum element size of 3 mm, resulting in approximately 168000 nodes and 47000 elements, suitable for simulations up to 4000 Hz (Figure 2.a). The properties of R290 refrigerant at 50°C were density ρ = 29.75 kg/m³ and speed of sound c = 253.8 m/s. An anechoic radiation boundary was considered on port A and a surface velocity of 1 m/s was prescribed on port B (Figure 2.b). We used the direct solver of ANSYS harmonic simulation, from 1778 Hz to 2239 Hz with 200 solution intervals.

After a few shape optimization rounds, we obtained the transmission loss (TL) results shown in Figure 3. One can observe the two TL peaks, suggesting an appropriate filtering on problematic frequencies of 1899 Hz and 2031 Hz. Further investigation of the pressure distribution along the muffler also showed a consistent behavior of high values located in the first tube and first volume (Figs. 4.a and 4.b).



(a) **(b)**

Figure 2. Mesh used on preliminary simulations with rigid wall (a). Fluid body configuration with locations of boundary conditions (b)

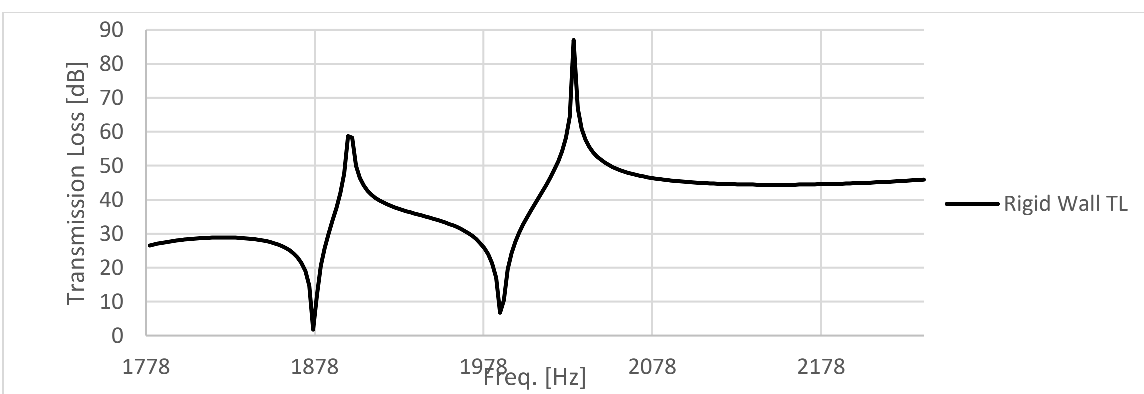
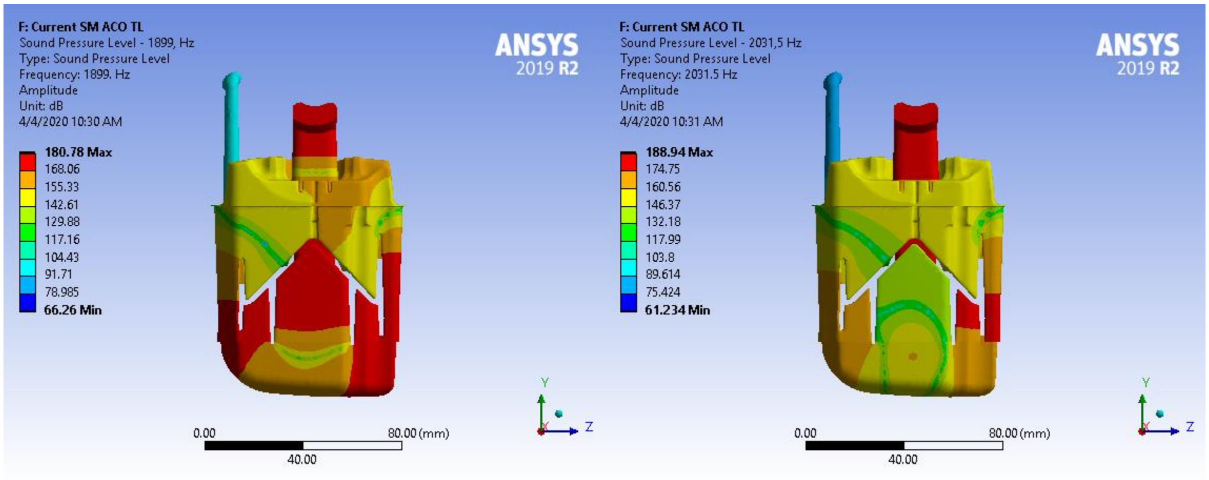


Figure 3. Transmission Loss of preliminary simulation, considering rigid walls and a slight shape optimization.

Thus, we proceeded to prototype and test this first optimized muffler, to assess its performance on a running compressor. We used the same experiment conditions for comparison purposes. Results are shown on Figure 5.



(a) **(b)**

Figure 4. Pressure distribution of rigid wall muffler at 1899 Hz (a) and 2031 Hz (b).

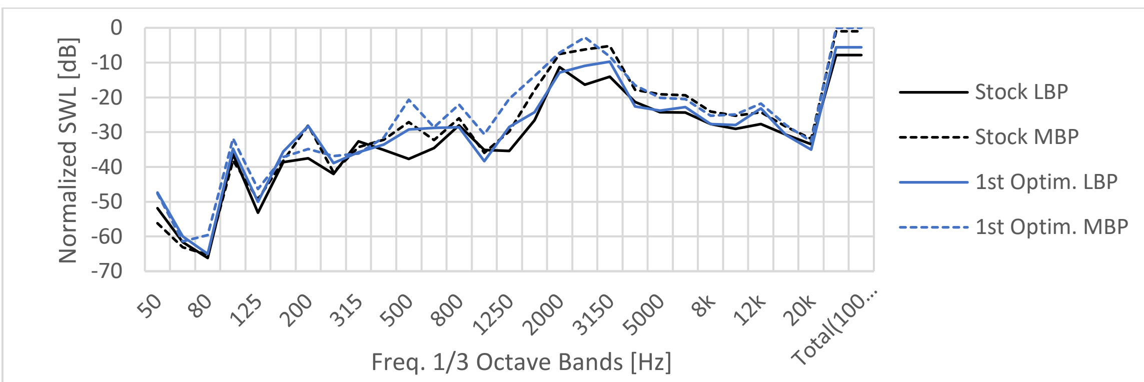


Figure 5. Comparison of normalized sound power level between first muffler attempt and stock muffler. Same CECOMAF conditions of low back pressure (LBP) and medium back pressure (MBP) were used.

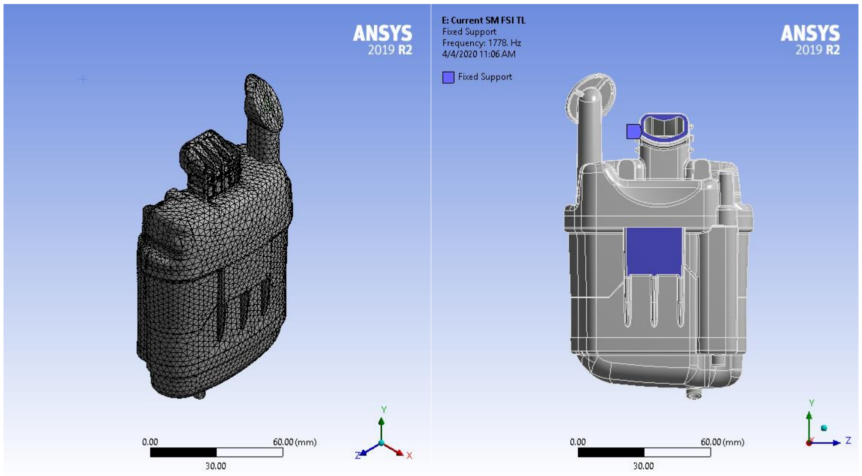
It was clear the results from our standard approach was insufficient to represent the reality, since we were unable to achieve any improvements at 2000 Hz band. Therefore, we started focusing in a more robust approach, considering FSI.

3.1. Simulations considering FSI

To consider the flexible walls, we added the muffler's structural part, increasing the mesh size to 114000 elements (Fig. 6.a). The polymer used to prototype our suction muffler was polyketone, with approximate mechanical properties of Young's modulus E = 8.2 GPa, Poisson's ratio ν = 0.35, and density ρ = 1480 kg/m³. We also considered the fixed support boundary conditions on surfaces marked by the blue color in Figure 6.b.

All other configurations used on the simulation remained the same as with rigid body model, for comparison purposes. The transmission loss spectrum from both approaches can be observed in Fig.7.

PAPER ID: 0395
DOI: 10.18462/iir.compr.2021.0395



(a) **(b)**

Figure 6. Structural mesh used in FSI simulations (a) and fixed support boundary conditions (b).

It is safe to say that, just by adding the effects of flexible wall, for this type of muffler, the transmission loss spectrum changes significantly. These changes on transmission loss were also observed by (Corral, Floody, & Venegas, 2016) and (Xu, Zhang, Ge, & Liu, 2019). The first peak of 1899 Hz was shifted to 1876 Hz and decreased in amplitude. The peak of 2031 Hz disappeared completely. A slight decrease of all spectrum amplitudes can also be observed.

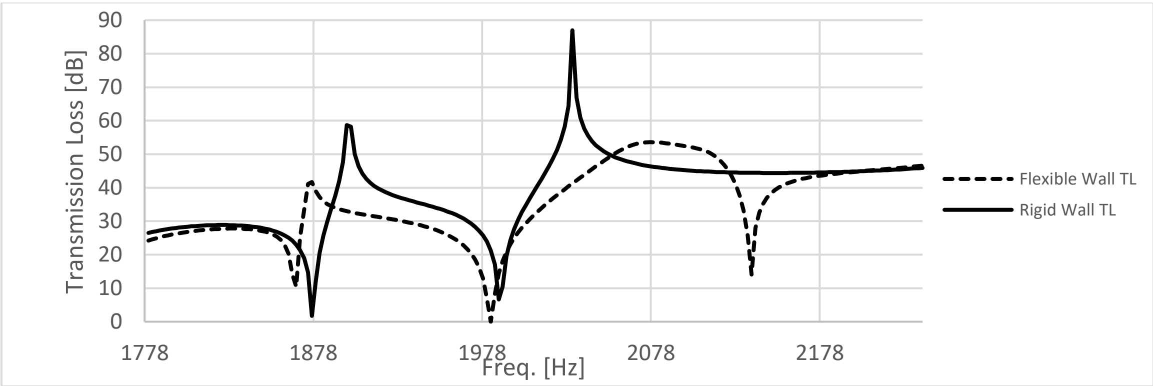
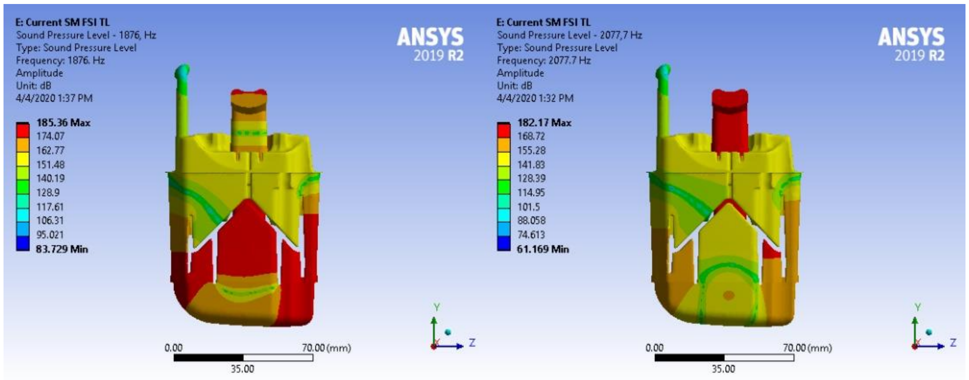


Figure 7. Transmission loss between flexible and rigid wall models of the same first optimized shape attempt of suction muffler.

Although, a similar behavior of pressure distribution can still be observed with the FSI approach (Fig. 8.a and b). The highest-pressure values continued to occur at the muffler's first pipe and first volume.

DOI: 10.18462/iir.compr.2021.0395



(a) **(b)**

Figure 8. Pressure distribution with flexible walls at 1876 Hz (a) and 2077 Hz (b).

On the other hand, this model allows to calculate an equivalent radiated power from the external surfaces of structural part, shown on Figure 9.

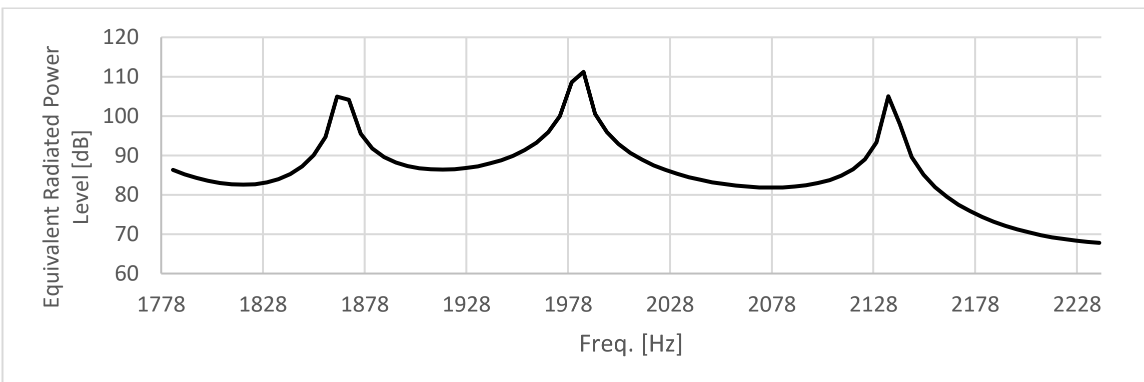


Figure 9. Equivalent radiated power level by muffler's flexible walls made of Polyketone.

This information raised the concern that the compressor's cavity may also being excited by muffler walls, and not just by its outlet (port A described in previous section). Hence, we also took this mechanism of excitation into consideration on further shape optimization steps.

After obtaining a new optimized shape for the suction muffler through a heuristic process considering FSI, the device was prototyped with the same polymeric material and tested. The optimized muffler performance as means of transmission loss will not be shown in this paper to respect the company interests. Again, we used the same CECOMAF conditions of low back pressure and medium back pressure for comparison purposes. Results are shown in Figure 10.

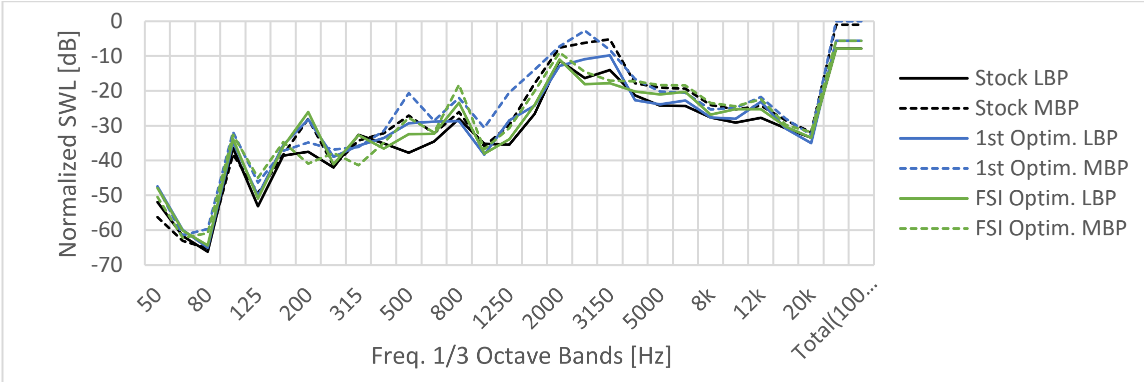


Figure 10. Comparison of normalized sound power level between previous configurations and FSI optimized muffler. Same CECOMAF conditions of low back pressure (LBP) and medium back pressure (MBP) were used.

Although LBP results showed little change at normalized SWL, we were able to achieve 1.5 dB of noise reduction at 2000 Hz in MBP.

It became clear that the application of methodology, using a model which considers FSI along with heuristic optimization, was successful at achieving the noise reduction on the problematic frequency bands.

4. FINAL REMARKS

The limitations of a rigid wall model were presented and discussed. It was shown that, for this configuration of muffler, made of a polymeric material, the structure can change significantly its filtering behavior. Experimental results were shown, corroborating the ineffectiveness of the muffler optimized via a standard approach, even with a suitable transmission loss response.

Then, a new approach was proposed, with a model that considers flexible walls and fluid-structure interaction. This approach has proven to be much more reliable, delivering a consistent noise reduction at the problematic one-third frequency bands of 2000 Hz, 2500 Hz and 3150 Hz.

We would recommend further investigation on the sensitivity of fluid-structure interaction, so these effects are more easily understood, and can be taken into consideration on the first steps of a muffler design. It would also be interesting to use some optimization algorithm, capable of minimizing both outlet pressure and structural vibration of the muffler. Finally, further research on the sensitivity of the polyketone mechanical properties would also have meaningful value to understand this material's limitations for the present application.

ACKNOWLEDGEMENTS

We would like to acknowledge the financial aid and infrastructure given by Secop Austria GmbH for carrying out this research.

DOI: 10.18462/iir.compr.2021.0395

NOMENCLATURE

FSI	fluid-structure interaction	*LBP*	low back pressure CECOMAF cond.
FE	finite element	*MBP*	medium back pressure CECOMAF cond.
E	Young's modulus (GPa)	ν	Poisson's coefficient
ρ	density (kg/m^3)	*c*	speed of sound (m/s)
SWL	Sound Power Level		

REFERENCES

Choi, K. K., Dong, J., Vlahopoulos, N., Wang, A., & Zhang, W. (2003). Parametric design sensitivity analysis of high frequency structural-acoustic problems using energy finite element method. *ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference.* Chicago.

Corral, L., Floody, S., & Venegas, R. (2016). Muffler shape optimization accounting for acoustic- structure interaction. *22th International Conference on Acoustics.* Buenos Aires.

Nikam, A. R., & Ulhe, P. N. (2015, July). Automobile muffler design for better structural integrity using fluid structure interaction. *International Journal of Research in Aeronautical and Mechanical Engineering*, 17-23.

Soize, C., & Michelucci, J. C. (2000). Structural shape parametric optimization for an internal structural-acoustic problem. *Aerospace Science and Technology*, 263-275. doi:10.1016/S1270-9638(00)00135-8

Xu, J., Zhang, J., Ge, J., & Liu, Z. (2019). Acoustic-structure Coupling Analysis and Optimization of Muffler. *IOP Conference Series: Materials Science and Engineering, 612*, 32-84. doi:10.1088/1757-899x/612/3/032084