Numerical and Experimental Modelling of Structure-borne Aircraft Interior Noise

Krylov, V.V.[1], Georgiev, V.B.[2], Jensen, K.A.[3]
[1] Professor, Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
[2.] Research associate, Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK
[3] Student, Department of Aeronautical and Automotive Engineering, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK

Abstract

In the present paper, the problem of structure-borne interior noise generated in an aircraft cabin has been considered using a simplified reduced-scale model of a passenger aircraft. Experimental investigations included measurements of frequency response functions at several positions of a microphone inside the aircraft, when an electromagnetic shaker exciting structural vibrations was located at different places. Numerical investigations have been carried out as well, and they included finite element calculations of structural and acoustic modes as well as frequency response functions for interior acoustic pressure. Some of the obtained numerical results have been compared with the experimental ones. The observed reasonably good agreement between them indicates that structure-borne interior noise in the described reduced-scale aircraft model can be predicted and understood rather well. This demonstrates that the proposed approach employing simplified reduced-scale structural models can be used successfully for prediction and mitigation of aircraft interior noise.

Keywords: Aircraft interior noise, Structure-borne noise, Finite element modelling, Experimental modelling.

Численное и экспериментальное моделирование структурного внутреннего шума самолета

Крылов В.В.[1] , Георгиев В.Б.[2], Дженсен К.А.[3]
[1] Профессор, Кафедра авиационной и автомобильной техники, Университет Лафборо, Лафборо, Лестершир, LE11 3TU, Великобритания
[2] Научный сотрудник, Кафедра авиационной и автомобильной техники, Университет Лафборо, Лафборо, Лестершир, Великобритания
[3] Студент, Кафедра авиационной и автомобильной техники, Университет Лафборо, Лафборо, Лестершир, Великобритания

Аннотация

В данной работе рассматривается проблема структурного внутреннего шума, создаваемого в кабине самолета, с использованием упрощенной модели уменьшенного масштаба пассажирского самолета. Экспериментальные исследования включали измерения функций частотного отклика в нескольких положениях микрофона внутри самолета, когда электромагнитный вибратор возбуждал структурные колебания в разных местах. Проведены также численные исследования, включающие в себя расчеты методом конечных элементов структурных и акустических мод, а также функций частотного отклика для внутреннего акустического давления. Некоторые из полученных численных результатов были сопоставлены с экспериментальными. Наблюдаемое достаточно хорошее согласие между ними указывает на то, что структурный внутренний шум в описанной модели самолета с уменьшенным масштабом может быть предсказан и хорошо понят. Это демонстрирует, что предлагаемый подход, использующий упрощенные структурные модели уменьшенного масштаба, может быть успешно использован для прогнозирования и уменьшения внутреннего шума самолета.

***Ключевые слова**: Внутренний шум самолета, Структурный шум, Моделирование методом конечных элементов, Экспериментальное моделирование.*

E-mail: V.V.Krylov@lboro.ac.uk (corresponding author), V.B.Georgiev@lboro.ac.uk, K.Jensen@lboro.ac.uk

Introduction

Over the last decades, attention has been paid to investigations of structure-borne interior noise in aircraft and road vehicles (see e.g. [1-6]). Excessive noise levels can create an unacceptable noise environment, causing passenger discomfort, interference with communication, crew fatigue and malfunction of equipment. Different approaches can be used to predict structure-borne interior noise in vehicles and aircraft. These approaches show different levels of success, and their areas of application depend on frequency ranges being looked at. The main current approaches include Finite Element Method (FEM) and Statistical Energy Analysis (SEA). It should be noted that it can be difficult to apply FEM for real structures due to the complexity of the structures involved. It is often more practical to use FEM on simplified structural models, which can be carried out at relatively low frequencies. Application of SEA requires a high modal density, and therefore it is usually useful only at higher frequencies. Reduced-scale simplified modelling is an alternative and promising approach to studying structure-borne interior noise in aircraft and road vehicles [7-13]. Using reduced scale simplified models of aircraft and vehicles, experimental measurements and numerical calculations can be carried out in order to predict structure-borne interior noise in real vehicles and aircraft.

In comparison with the case of road vehicles, reduced-scale simplified modelling has been in limited use for studying aircraft interior noise so far. For example, numerical calculations for a simplified reduced-scale model combined with the experimental measurements were carried out for a part of a fuselage [7]. It should be noted in this connection that structure-borne noise in aircraft can be generated by a variety of sources. The main source is unbalanced forces from engines located on wings. Other sources of aircraft structure-borne noise can be wakes on the surfaces of the wings, air conditioning systems, hydraulic pumps, effects of jet and boundary layer, etc. [5, 6]. Whereas most investigations of noise inside aircraft cabins concentrated on regular-shaped enclosures, such as plain cylinders, authors of the paper [14] looked at irregular fuselage shapes. Such shapes were formed by circular cylindrical shells and flat metal sheets welded inside the shell to simulate the cabin floor. Measurements were carried out by applying an electromagnetic shaker and using accelerometers to measure the response of the structure. Research has been carried out also into the ability of FEM to predict the modes in actual fuselage structures [15]. The observed inaccuracies were associated with the need for refinement of the model at the interface between skin and stringers.

Development of simplified reduced-scale models of entire aircraft is a relatively unexplored area. As was mentioned above, there have been a limited number of studies done into noise associated with parts of fuselage structures [7, 14, 15]. However, comparisons with real measurements show that ignoring some parts of aircraft structures, especially wings, results in substantial errors. Therefore, the development of more informative reduced-scale aircraft models capable of simulating different types of aircraft structures would greatly enhance the modelling process. With the noticeable progress in reduced-scale modelling of vehicle interior noise [9-13], there may be a clearer way for developing reduced-scale noise modelling for aircraft applications. An important aspect following from the above is the need to model the entire aircraft, and not just the portions of interest.

In the present paper, the results are reported on combined experimental and numerical investigations of structure-borne interior noise in a simplified reduced-scale model of the entire aircraft.

1. Reduced-scale Model of the Aircraft

1.1. Scaling of the Model

The scaling of the model is an important issue that requires attention if there is any expectation from the model to describe a real aircraft structure. In purely acoustic models, scaling follows the law that, if the linear dimensions are reduced by N times, the increase in resonant frequencies will also be by N times. Vibration fields in structures are combinations of different types of elastic waves, and scaling laws are less obvious for structural models. It can be proven though that, if all linear dimensions are scaled, i.e. length, width and height of the model and, which is especially important, thickness of the material, are reduced by N times, then the resonant frequencies will again increase by N times. This law is valid not only for simple plate-like structures, but also for structures of any complexity. If this were not the case, reduced-scale structural-acoustic modelling would be useless. Scaling is not valid for structural and acoustic attenuation due to complex physical mechanisms of energy loss. Therefore, in studies involving reduced-scale models damping is usually neglected.

1.2. Development of the Aircraft Model

A reduced-scale simplified model of an entire aircraft has been designed and developed specifically for this investigation. The model was based and scaled from the major dimensions of the passenger jet A330-200. The model has been simplified as much as possible to ease manufacturing costs and time, and it utilised the lowest level of complexity that such a model would require. The scaling of the developed aircraft model was 1:50. Essentially the model was made up from a tube of circular cross-section, modelling the fuselage, and a wing section cut from a metal plate. The wings were simple swept wings also manufactured from flat steel plate. Both starboard and port wings were welded to a centre section, so that they formed a continuous wing structure. This wing structure passes through the fuselage, and it is welded into position on the fuselage. Masses were attached to the wings to model the engines. A vertical control surface was also attached to the fuselage. This surface was also made from sheet steel and welded to the fuselage. At each end of the fuselage, circular end plates were welded in place to provide the cabin's enclosed volume. All acoustic measurements were to be taken in this enclosed space. The model was also manufactured with the possibility of a cabin floor being built into it. Figure 1 shows a picture of the aircraft model design. This picture was drawn using the MSC/NASTRAN finite element software, and it shows that the model is vastly simplified in comparison with the real case.

Even though the model is vastly simplified, it was important to copy certain aspects of the structure as close to the real case as possible. If the model structure is nothing like the real case, it will not react in the same way that the real aircraft would. Every attempt was made to copy the structure as closely as possible, within reason, throughout the development process. Aspects of the design that needed to be similar included: accurately scaled dimensions from the real case; materials as close as possible to the real case without the cost becoming excessive; and similar main structure to the real case, including structural layout and material thickness. The limitations of manufacturing techniques also provided some constraint, especially concerning the thickness of materials used.

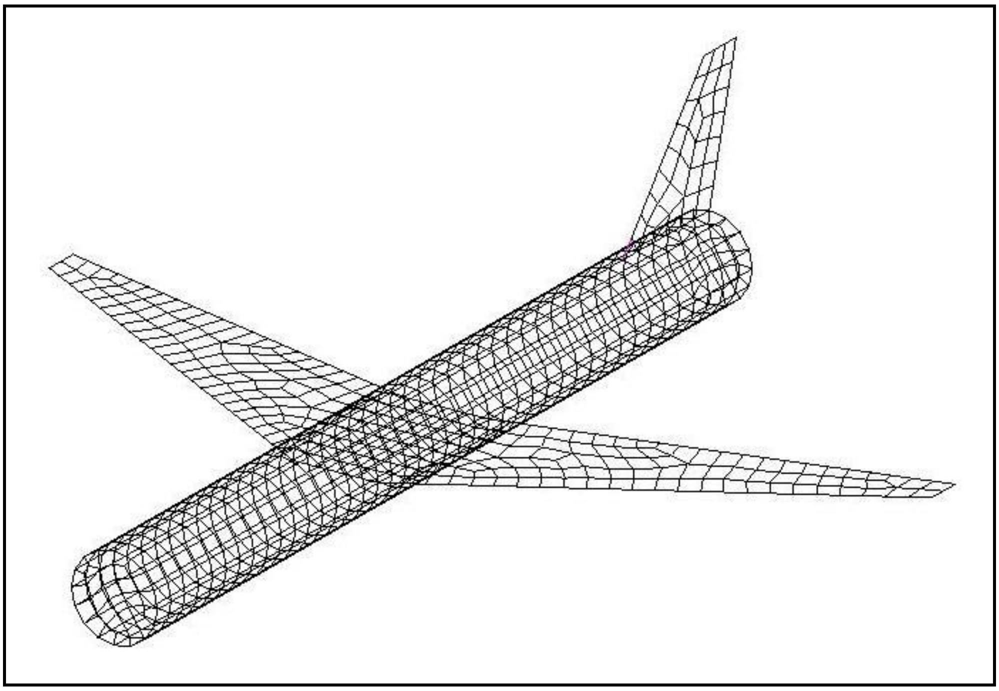

Fig. 1. A simplified aircraft model drawn using MSC/NASTRAN software

The aircraft model was constructed entirely from sheet steel. The wings and fin have been manufactured from 2 mm sheet steel and welded to the fuselage. On real aircraft, the wings and stabilisers are considerably stiff to carry the large lift loads produced. Therefore, the wings and fin have been made of a thicker material than the fuselage to make them stiffer. The fuselage was produced from 1 mm thick sheet steel as this is the thinnest material that could be welded. The end plates were also manufactured from 1 mm sheet steel and welded to each end of the fuselage. It was felt that welding of all joints would be best to simulate the real case. Using nuts and bolts was felt to be inappropriate as the connections provided would not be as similar to the real case as desired.

The masses attached to the model to simulate the engines were placed according to the scaling from the real aircraft and were approximately 10% of the overall weight of the aircraft. Figure 2 shows the manufactured aircraft model that was experimented on.

1.3. Finite Element Calculations

In addition to experimental measurements, finite element calculations of structure-borne interior noise were carried out for the reduced-scale aircraft model under consideration. The methodology was the same as the one earlier used by some of the present authors for calculations of structure-borne interior noise in simplified reduced-scale models of road vehicles (see e.g. [11-13]). The aircraft model under consideration was drawn in MSC/PATRAN standard package and then imported for the calculations to be carried out using MSC/NASTRAN software. The amplitude of the force applied from the electromagnetic shaker was equal to 2.6 N. This value of the force was used in all numerical calculations.

Fig. 2. The manufactured aircraft model placed on the laboratory table

2. Experimental Setup and Procedure

2.1. Equipment Used

All measurements have been carried out in the Noise and Vibration Laboratory at Loughborough University. Sound Pressure Level (SPL) inside the aircraft compartment was measured using a condenser microphone. The amplifier used for the microphone was a Bruel & Kjaer Type 5935 amplifier. The accelerometer used was a Bruel & Kjaer Type 4344. The accelerometer was connected to the analyser through a charge amplifier. The amplifier used was a Bruel & Kjaer Type 2365. A Bruel & Kjaer Type 8200 force transducer was also used during testing. This was connected to the analyser in the same way as the accelerometer through a Bruel & Kjaer Type 2365 charge amplifier. The force transducer was attached to the electromagnetic shaker via a push rod. The shaker used was a Ling Dynamic Systems 200 series. All measurements were recorded using a Hewlett Packard (HP) 3566 FFT analyser.

2.2. Model Support

In normal operation conditions, the ways that aircraft are supported are very different from the case of road vehicles. Vehicles are supported by their four wheels, but an aircraft in flight is supported by distributed lift forces. As a simple approximation, it could be said that it is held in the air by two points on the wings. These are called the centre of lift of the wing. Unfortunately, suspending the model aircraft from these two points was impractical, and consequently other methods had to be considered. Even though suspending the model would best reflect the real case, the possibility of testing the model while resting on foam on a flat area as well as other positions were also investigated. Finding a suitable method to securely attach the model was a challenge. Finally, it was decided that it would be best to test the model while suspending it over the fuselage. This decision was made after some initial measurements that were taken in each position. Figure 3 shows the suspension method used for the model aircraft. This method allowed the easiest attachment of the shaker and also made inserting the microphone into the interior especially easy.

Fig. 3. The manufactured reduced-scale aircraft model supported by suspensions

2.3. Experimental Procedure

Hann windowing was used, and thirty averages were taken for each data recording. Because the aircraft model was scaled by a large amount, the frequency range that the data is measured over needed to be increased. The frequency range of 0 to 3200 Hz was used for the aircraft model testing.

The number of parameters that could be varied during the model aircraft testing was somewhat limited. This was due to the limited number of places the shaker could be reliably attached to and also due to the size of the model interior. The interior compartment of the aircraft was relatively small and hard to access, and consequently it was not possible to further the investigations using inserted damping materials. Subsequently, the two aspects of the testing procedure that were varied were the shaker and microphone positions.

2.3.1. Microphone and Accelerometer Positions

It was decided to take readings at three points along the fuselage length. Two of the points were chosen at the front and rear of the interior compartment. The third point was chosen above the wing structure. Sound pressure levels as functions of frequency at all these three points have been measured and analysed. An accelerometer was also placed on the top surface of the fuselage above these three positions. Figure 4 shows the three microphone positions investigated. Foam was used to fill the gap around the inserted microphone.

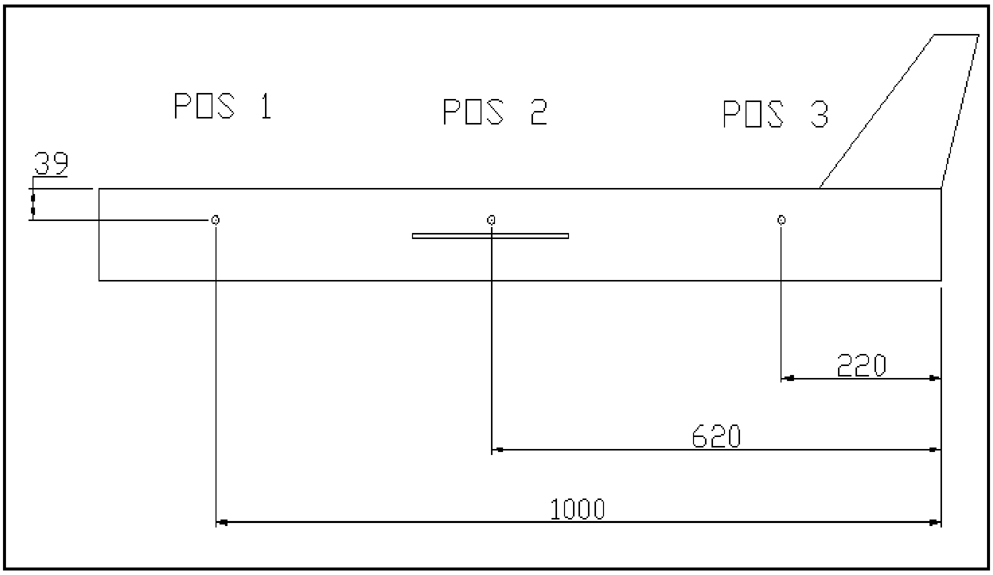

Fig. 4. Microphone positions inside the model aircraft (distances are in mm)

2.3.2. Shaker Positions

Three shaker positions have been selected. Two of them were on the wing: one at the engine and the other at arbitrary point on the wing. The third shaker position was on the fuselage. Unfortunately, due to the curvature of the fuselage and the flat contact surface of the shaker it was difficult to obtain good contact between them, which was affecting the results. The three shaker positions are shown in Fig. 5.

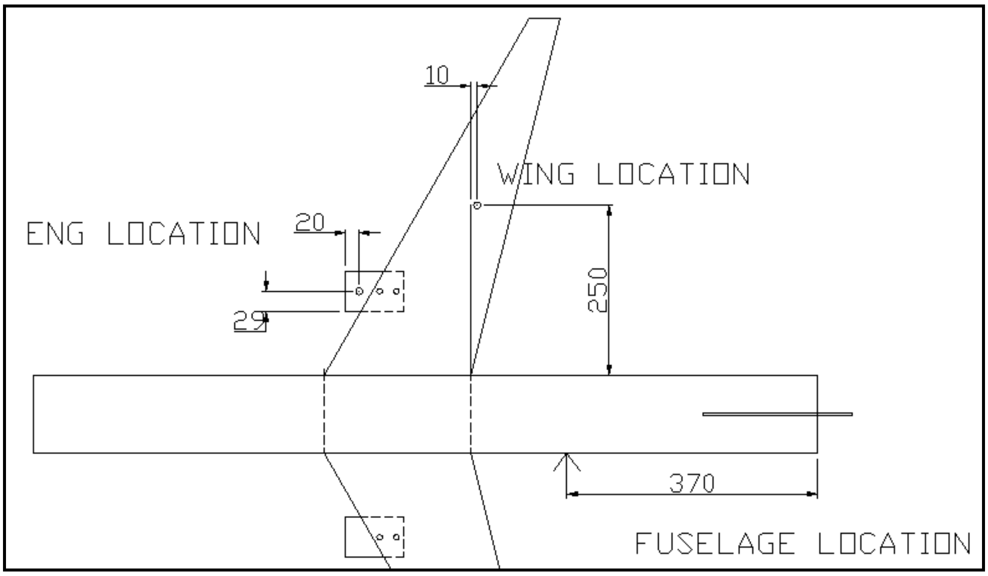

Fig. 5. Positions of the electromagnetic shaker on the aircraft model (distances are in mm)

3. Experimental Results

3.1 General Remarks

The testing procedure included a number of initial testing phases as well as main measurements. The data was collected using the analyser in the laboratory and then was exported into Matlab. Aspects of the data that were of particular interest were the sound pressure level (SPL) within the aircraft model interior, the point mobility, and the coherence of the data.

3.2 Effect of Microphone Positions

Figure 6 shows the values of SPL measured by a microphone located in the position 1 - at the front part of the aircraft model, and in the position 2 - over the wing structure. The electromagnetic shaker was located at the wing. It can be seen from Fig. 6 that the behaviour of SPL is generally similar for both positions, except frequencies between 500 and 1500 Hz. The observed frequency peaks correspond to contributions of structural and acoustic modes.

Figure 7 shows a comparison between the values of SPL measured by a microphone located in the position 1 - at the front part of the aircraft model, and in the position 3 - at the rear part of the aircraft model. The electromagnetic shaker in these cases was also located on the wing. It can be seen that SPL at these two microphone positions also exhibit very similar behaviour. Once again, the region between 500 and 1500 Hz is of interest. In this region the position 3 data shows slightly higher peaks, whereas the position 1 data tends to shows slightly higher sound levels in all other areas.

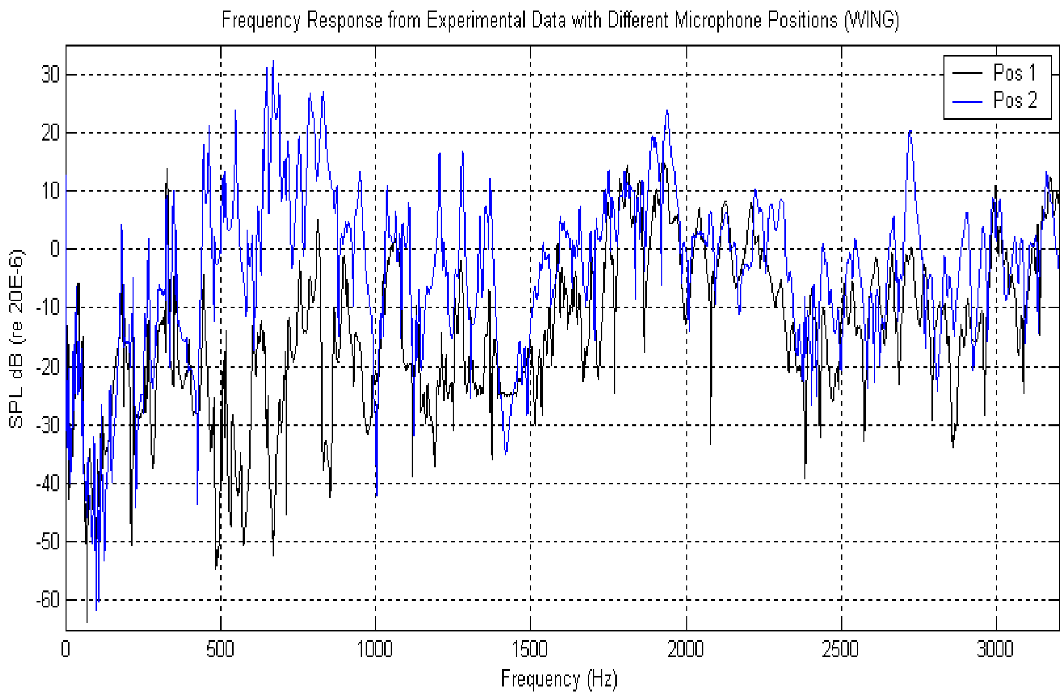

Fig. 6. Measured SPL at the microphone positions 1 and 2 for a shaker located on the wing

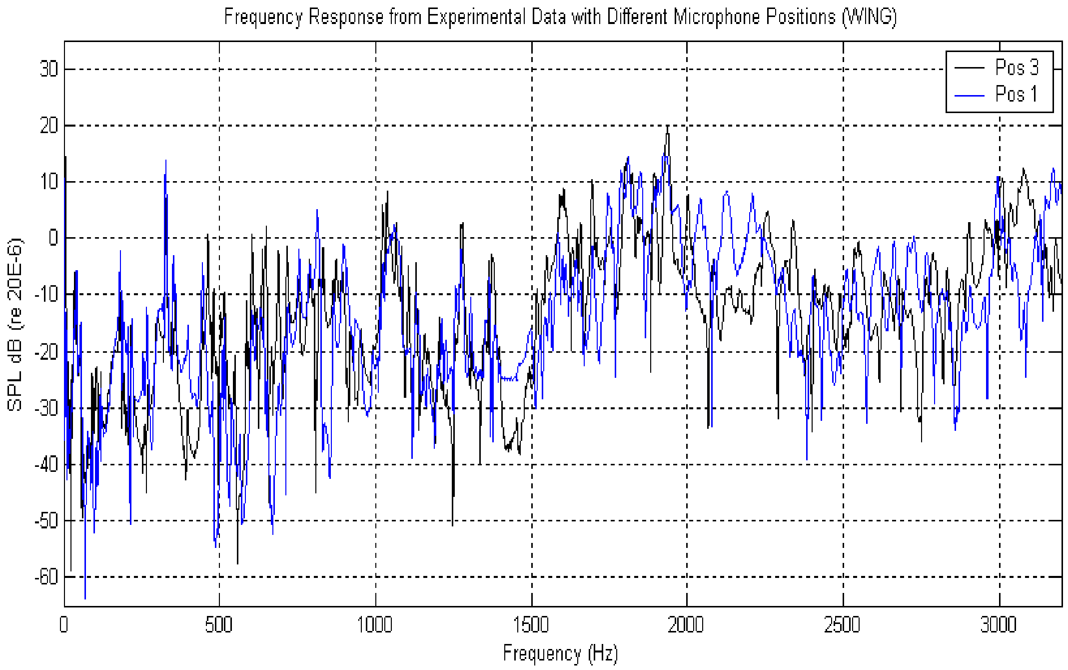

Fig. 7. Measured SPL at the microphone positions 3 and 1 for a shaker located on the wing

The results of the numerical calculations of SPL for the microphone positions 1 and 2 subject to the excitation by an electromagnetic shaker located on the aircraft wing are shown in Fig. 8.

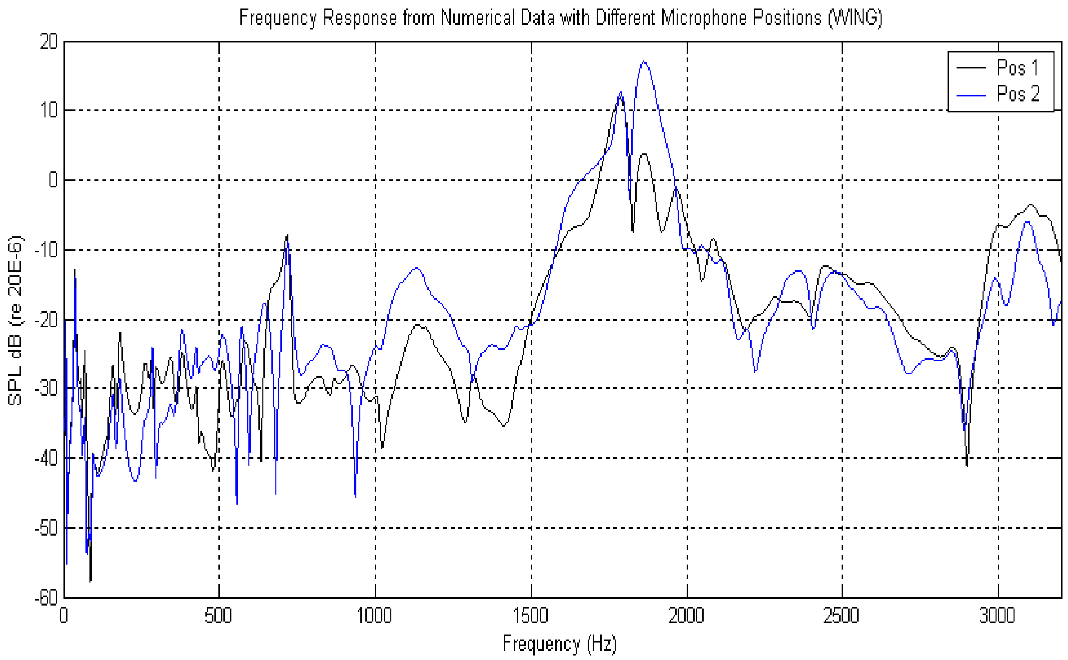

Fig. 8. Numerically calculated SPL for the microphone positions 1 and 2 (Wing Shaker)

It can be seen from Fig. 8 that the numerical results demonstrate very similar behaviour at the microphone positions 1 and 2. In both positions, there is an increase in SPL between 1500 and 2500 Hz, but not to the extent seen in the experimental data. This increase in SPL between 1500 and 2500 Hz is clearly visible, but it is much higher than in the experimental data. These differences could be due to FEM's inability to accurately model all details of the structure, especially around the centre of the fuselage. It also has to be taken into account that FEM only produces reliable results at low frequencies.

3.3 Effect of Shaker Positions

The aircraft model used in the experiments had a limited number of shaker locations to choose from. This was a result of the lack of easy points to mount the shaker to provide a variety of results. The two different shaker positions that are analysed below are at the engine and on the wing. Figure 9 shows the observed behaviour of SPL at the engine and wing shaker locations for the microphone position 2. Essentially the graphs are very similar, both showing similar oscillations with frequency. Also a large number of resonant peaks are common on both graphs, which is in agreement with the theory of structure-borne interior noise involving coupled structural and acoustic modes [9-11]. There is, however, a difference in sound pressure levels between the data from the wing and engine positions of the shaker.

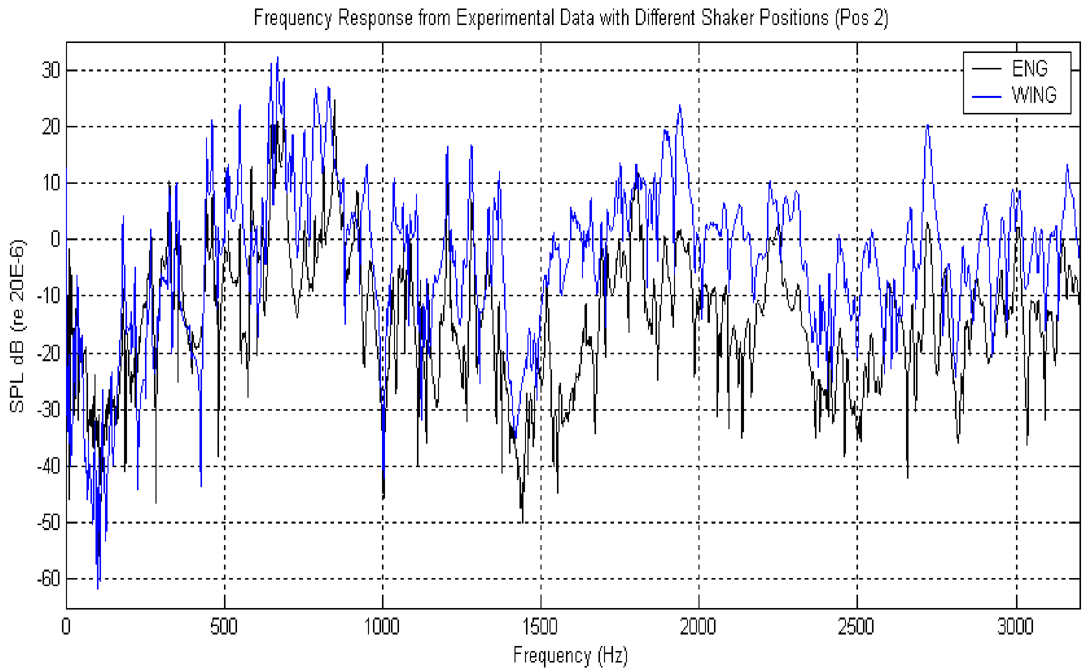

Fig. 9. Experimental SPL for different shaker positions (Microphone Position 2)

The observed SPL for the shaker located on the wing is on average by approximately 10 dB higher throughout the frequency range. This can be explained by the fact that a wing shaker location further out along the span corresponds to higher displacements in some structural modes of the entire aircraft, causing their more efficient excitation by a shaker [9-11]. This may account for the higher SPL. The same experimental data, but at the microphone position 1, are shown in Fig. 10. This figure is displaying the similar patterns, as expected.

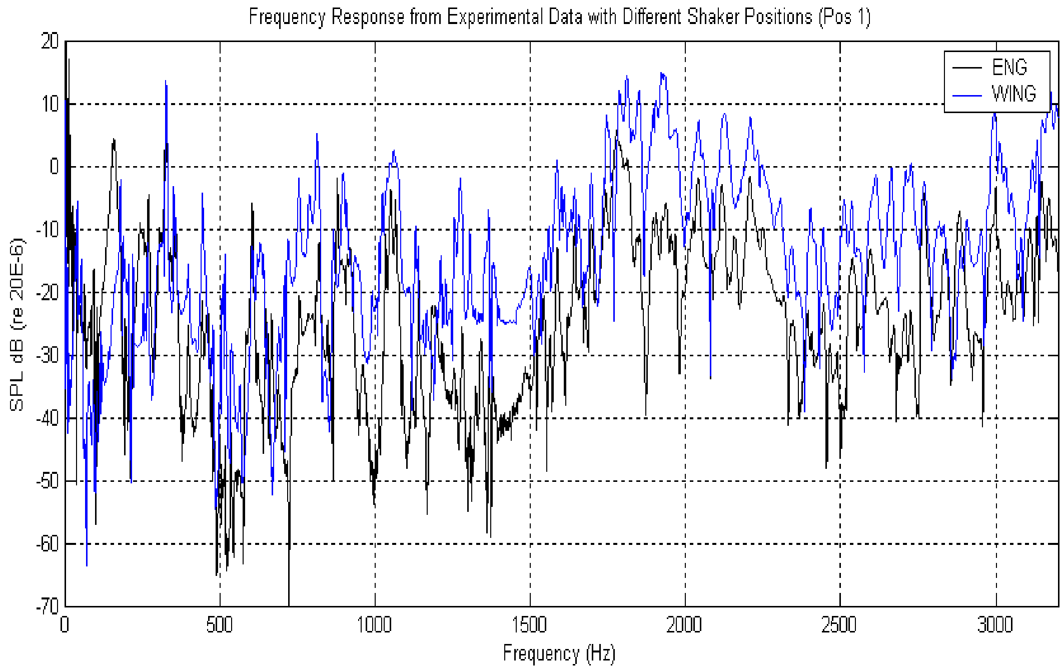

Fig. 10. Experimental SPL for different shaker positions (Microphone Position 1)

Figure 11 shows the numerically predicted SPL for the two different shaker positions - at the engine and on the wing. Surprisingly, a little difference between the results for the two shaker locations can be seen. Unlike the experimental data, the numerical data does not show higher sound levels associated with the wing shaker. The reason for that is yet unclear.

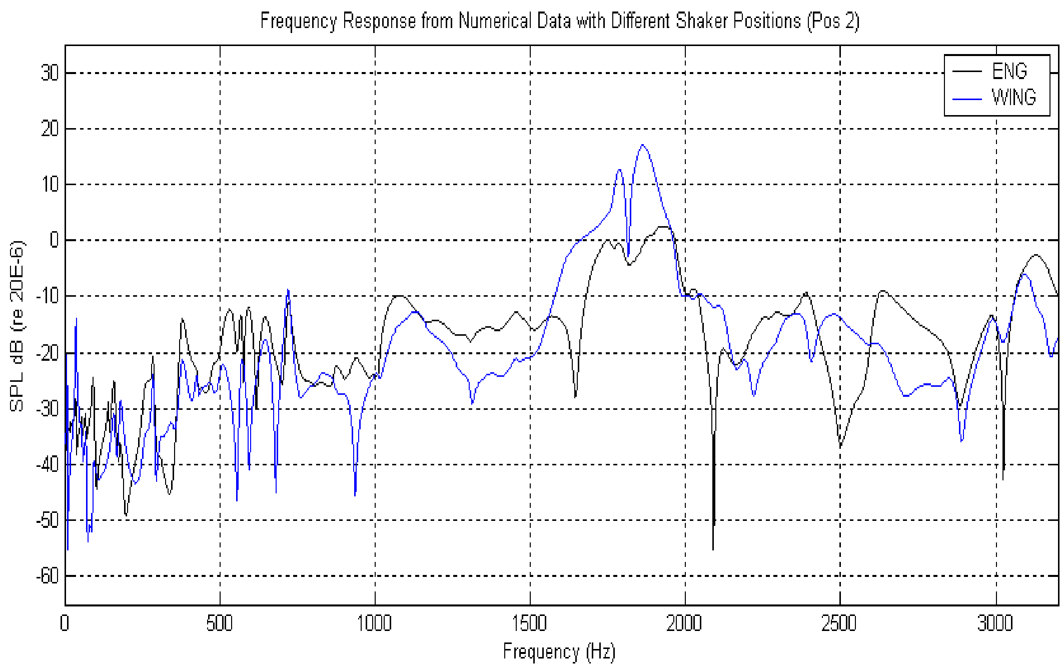

Fig. 11. Numerical SPL for two different shaker positions (Microphone Position 2)

4. Comparison of Experimental and Numerical Results

In what follows, a direct comparison is made between the experimental and numerical results for SPL inside the model aircraft cabin. Only the wing shaker position is used in this analysis. Let us first consider the experimental and numerical results obtained for the microphone position 3. The comparison of these results is shown in Fig. 12. The shapes of the two curves show very good similarity, with regions of elevated noise levels occurring in the same frequency ranges. The actual SPL for the experimental and numerical data shows good resemblance in most parts of the frequency range. The agreement between the numerical and experimental SPL is worse at the beginning and at the end of the entire bandwidth. Partly this could be explained by possible errors in collecting the experimental data at lower frequencies due to some problems with coherence. At high frequencies, the reliability of the numerical results from FEM is lower due to the influence of such factors as mesh size.

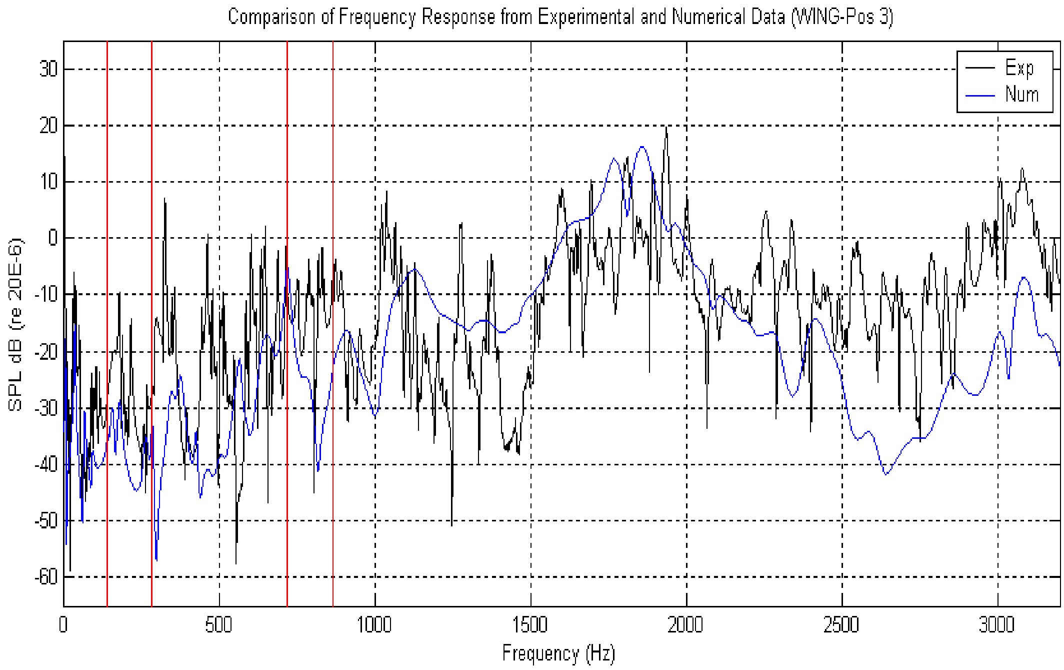

Fig. 12. Comparison of experimental and numerical data (Microphone Position 3)

Some frequency peaks from the numerical and experimental data have been plotted also in the zoomed-in view to see whether there is good correlation between them. The results are show in Fig. 13. One can see that there is a good correlation between the numerical and experimental peaks, thus showing the accuracy of the FEM at predicting the frequency response of the structure.

Figure 14 shows the numerical and experimental results that came from the microphone position 2. Up to 1500 Hz, the experimental data shows a peak in SPL. However, this trend is not mirrored by the numerical data, causing the predicted and measured noise levels to be very different in this range. Microphone position 2 is above the one-piece wing structure that passes through the fuselage. The observed discrepancy might be due to the fact that FEM is not describing this part of the aircraft model particularly well.

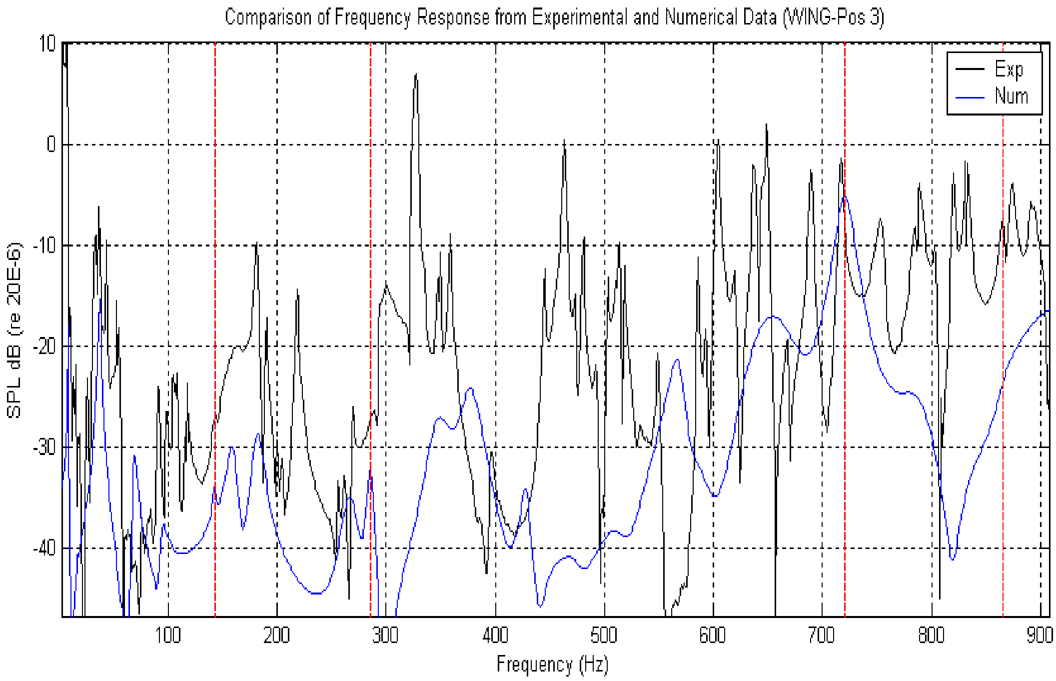

Fig. 13. Zoomed-in view of Fig. 12

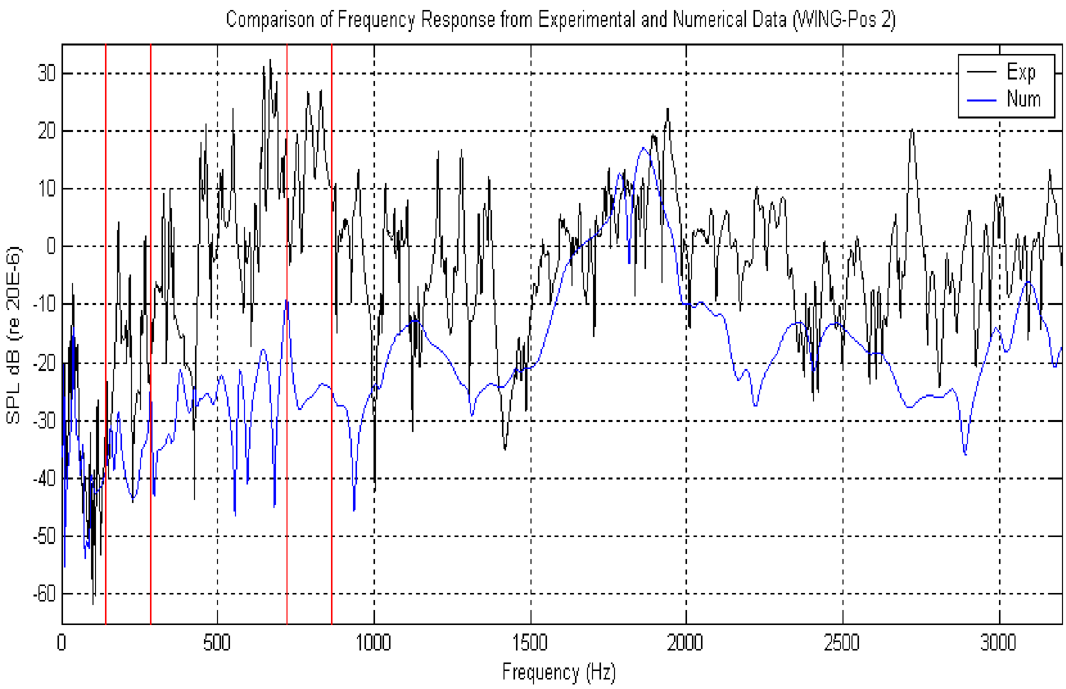

Fig. 14. Comparison of experimental and numerical data (Microphone Position 2)

Another possible reason for the differences between the results shown in Fig. 14 could be the way the model was supported during the testing. The model aircraft was suspended by ropes to try and mirror the ideal case. The finite element model might not reflect these suspensions correctly, which could have caused some discrepancies in the results. There may be also other aspects that could induce errors, such as geometrical differences between the real and numerical models.

The comparison between the numerical and experimental data at the microphone position 1 is similar to the case of the microphone position 3, and it shows a good correlation, as can be seen in Fig. 15. Overall, the correlation between the numerical and experimental results is quite reasonable, taking into account all the factors that could have degraded the results obtained.

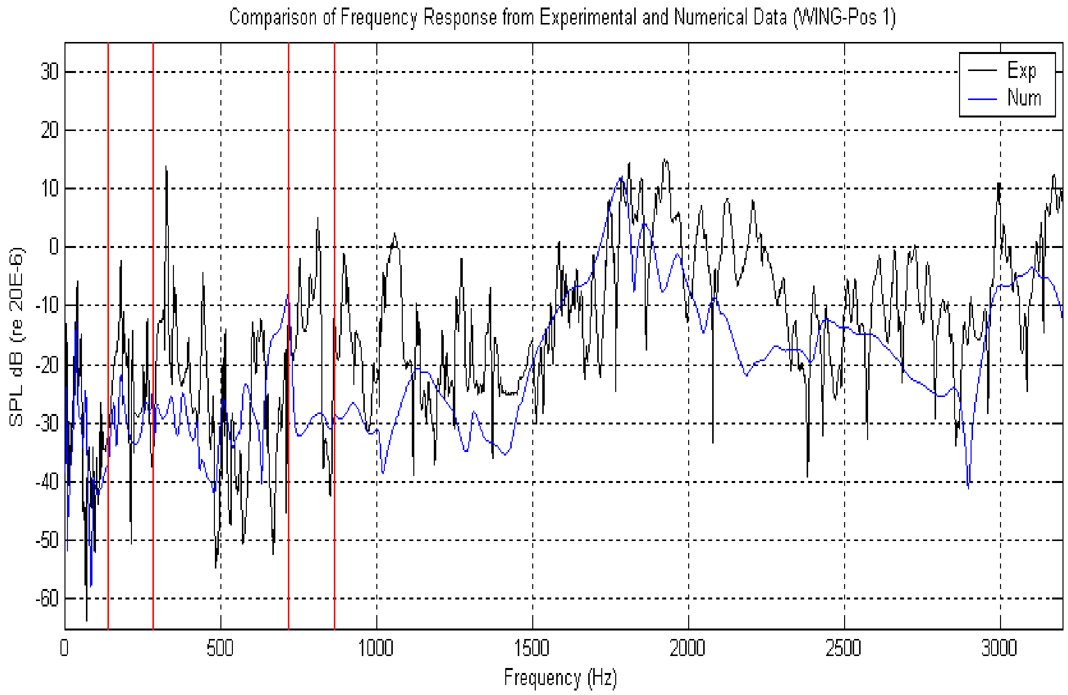

Fig. 15. Comparison of experimental and numerical data (Microphone Position 1).

5. Conclusions

The experimental results and the results of the numerical calculations of structure-borne interior noise in the simplified reduced-scale aircraft model under consideration have shown reasonably good agreement. This demonstrates that the combined experimental and numerical approach to investigation of structure-borne aircraft interior noise based on simplified reduced-scale structural models can be successfully used in practice.

The downside of using reduced-scale models for aircraft investigations is a too big scaling required in this case. Whereas typical road vehicle models are scaled as 1:4, the aircraft model described in this paper was scaled as 1:50. This resulted in the loss of many important structural details. A larger aircraft model would probably provide more practically relevant results and would allow a greater variety of tests to be carried out. But the larger the model the more unmanageable it becomes. However, even massively reduced-scale simplified aircraft models, like the one described in this paper, do show some promise, and their further investigations could make them more useful for practical applications.

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