APPLYING OF SIX-SIGMA METHODOLOGY FOR NOISE REDUCTION OF COMPLEX AEROSPACE ASSEMBLIES

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ABSTRACT

This paper shows that Six-Sigma methodology used in aerospace industry for controlling products' quality can be extrapolated to reduction of noise generated by complex aerospace assemblies.
In the last decades an important step forward was achieved in high-tech industries: the use of statistical methods for finding 'significant factors', which are responsible for low performances and quality of complex parts. Such a methodology is Six-Sigma. Using this methodology, the significant factors that affect the quality of a part are found and then appropriate solutions are applied for performance improving.
Noise emitted by a complex assembly can be considered a counter-performance of that assembly. Applying the Six-Sigma methodology the significant factors responsible for noise generating can be found. Then, appropriate solutions for noise level reduction are applied. Using of this methodology can generate surprising solutions for noise reduction which can complete the existing methods.

KEYWORDS: noise reduction, six sigma

NOMENCLATURE

p*, statistical parameter indicating the probability as a factor to be not significant for noise generated by an assembly, dimensionless
PPM, the number of manufactured assemblies which have emitted noise over upper specification limit, dimensionless
StDev(LT) (σ), standard deviation, for the noise emitted by assemblies during a long period of time, dimensionless
USL, upper specification level of emitted noise, [dB]
Y, measured noise emitted by an assembly, [dB]

$\bar{Y}$, mean value of noise, [dB]
Greek
Σ, the sigma level of noise generating process, dimensionless

1. INTRODUCTION

Extensive experience was accumulated in the field of statistical control of quality since the beginning of the XX century (W. Gosset ("Student"), W.A. Stewart, W. E. Deming).
In the last decades a new and important step forward was achieved in high-tech industries as aerospace industry: the use statistical methodologies for finding of the 'significant factors', which are responsible for low performances of complex parts. In the case of industrial parts, such performances are considered functional dimensions, final characteristics of material or heat and thermo-chemical treatments.
Initially, Six Sigma methodology was invented by engineer Bill Smith from Motorola in the early 1980s [1]. Taking into account quality management theories of Deming and Juran, Bill Smith intended to achieve a 10X reduction in product-failure levels in 5 years. After that the Six-Sigma methodology was adopted and developed by the most important aerospace companies [2].

The present paper shows that this methodology can be applied for the case of noise emitted by the complex assemblies (engine gearboxes, combustors etc.) targeting reduction of this counter-performance. The Six-Sigma methodology can be applied for noise reduction around airports too, but due to limited space, this subject cannot be presented in this paper due to limited space.

2. THE ESSENTIALS OF SIX-SIGMA METHODOLOGY

In the aerospace industry perfection of parts is more necessary than in other industries due to the high importance of aerospace components. These aerospace components enter the composition of complex assemblies of passenger aircraft as engines, landing gears, frames, electronic, electric, hydraulic and mechanical equipment.
During the design of an aerospace part the designer prescribes the appropriate tolerances for assuring the functionality and the desired performance of that part. However, during production process a lot of perturbing factors make as at the end of manufacturing process some of parts to not accomplish the prescribed quality and performance.
Assume an aerospace part having a characteristic C which must be under an upper limit C_{max}.
When the Six-Sigma methodology is applied, the target will be as more parts to have characteristic C under the limit C_{max}.
Applying of Six-Sigma methodology assumes application of a number of steps but the most important steps are:
-finding of significant factors influencing the value of characteristic C;
-acting on significant factors for decreasing the characteristic C under the limit C_{max}.
During applying of this methodology a specialized soft of statistics called MINITAB is used. This soft has all the instruments which are necessary for finding the significant factors and analyzing the effect of corrective actions for decreasing characteristic C under the limit C_{max}.

3. APPLYING OF SIX-SIGMA METHODOLOGY FOR REDUCTION OF NOISE EMITTED BY COMPLEX AEROSPACE ASSEMBLIES

3.1. General

Aeroacoustics is a new science which studies the basic causes responsible for generation of aerodynamic noise. It takes into account the noise produced by the main aerospace components but in general it cannot find quick solutions for the case of very complex aerospace assembly.
The noise generated by an aerospace assembly can be considered a characteristic of its quality like any other dimension or performance of that assembly. Obviously, this characteristic - level of generated noise can be improved, i.e. reduced as any other dimension or characteristic of that assembly.
Applying of Six-Sigma methodology for reduction of noise generated by a complex assembly can generate surprising solutions which can complete existing methods.
Using of the Six-Sigma methodology for noise reduction of assemblies consists of the following main steps:

Step no.1-Establishing of factors which could possibly influence the level of generated noise-issuing of the 'Cause-Effect' diagram

Step no.2-Measuring of generated noise and issuing of the 'Run-chart' and 'Capability Chart'

Step no.3-Finding the most significant factors through multiple linear regression

3.2 Description of Steps

For a clear understanding of Six-Sigma application in aeroacoustics, this paper provides a simple example for reducing of noise generated by a simple gearbox (fig.1) [3].

Step no.1-Establishing of factors which could possibly influence the level of generated noise-issuing of the 'Cause-Effect' diagram

During this first step, a team of engineers expose their opinions about the factors which could have an influence on the noise generated by the analyzed assembly, in this case the gearbox assembly presented as an example in fig.1.
The result of this analyze can be presented in a diagram called 'Cause-effect diagram' which can be generated by the MINITAB (fig.2). [4]

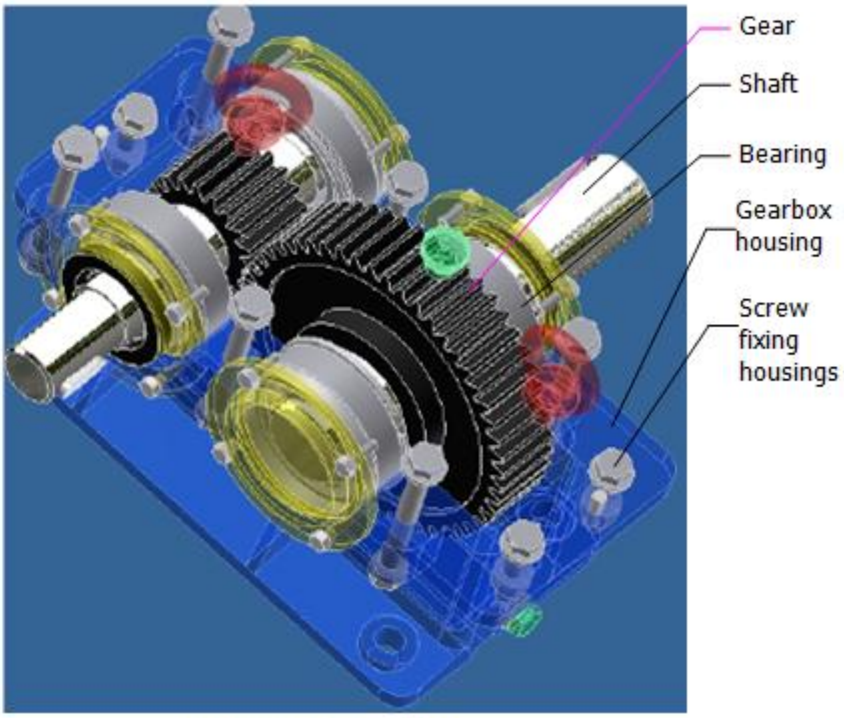


Figure 1: Gearbox assembly

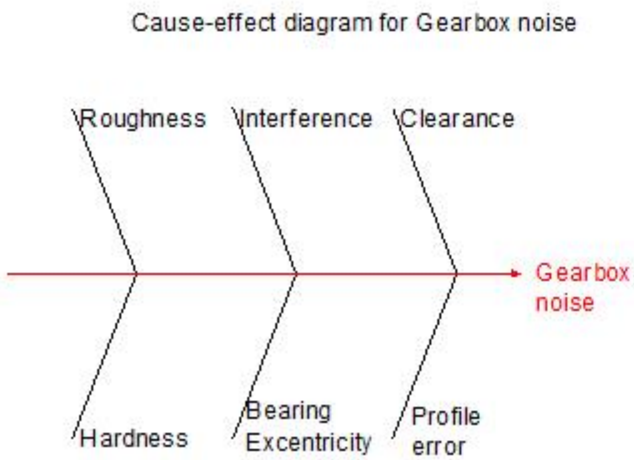


Figure 2: Cause-Effect diagram

This diagram shows graphically the dependence between noise level Y (dB) and the possible factors which are responsible for noise generation: X_i, i=1…n.

In fig. 3 one can see that specialists indicated as possible factors the following characteristics of gearbox components:

X1 [mm] is the clearance between teeth

X2 [·m] is the profile error of teeth

X3 [·m] is the is the eccentricity of inner ring of bearing
X4 [HRC] is the hardness of teeth surface
X5 [·m] is the roughness of teeth surface
X6 [mm] is the clearance between the bearing diameter and the appropriate reaming in gearbox housing

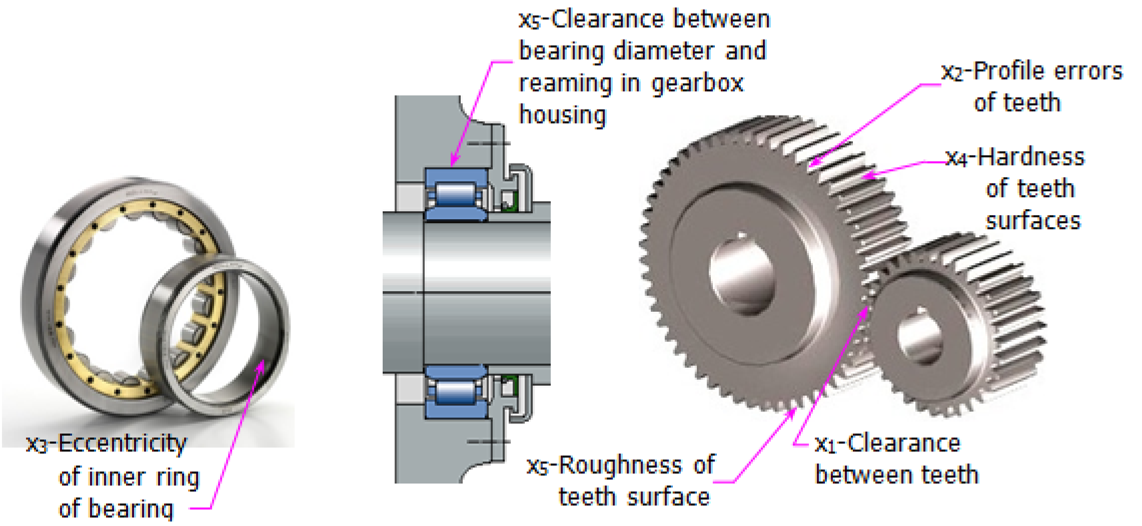
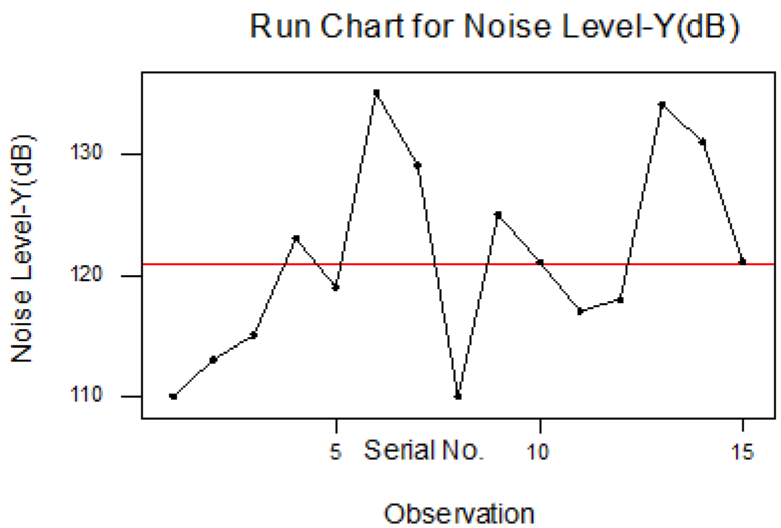


Figure 3: Factors which could have influence on noise generated by gearbox assembly

Step no. 2-Measuring of generated noise and issuing of the 'Run-chart' and 'Capability Chart'

During production of gearbox assemblies, the total noise radiated by each gearbox can be measured in an anechoic room. Then, using MINITAB is created a 'Run-Chart' (fig.4). This graph shows the noise level Y (dB) as a function of serial number of gearbox (No.).
For the analyzed case, the noise level of 15 subsequently manufactured gearboxes is presented in the graph from fig.4. In this case, the parameter is serial No. of gearbox ranging from 1 to 15 and the function is noise level, Y (dB), ranging from 110 to 135 dB. Seeing this graph, one can establish as a target reduction of noise generated by a gearbox under the upper specification limit USL=130 dB.



Number of runs about median:	9.00000	Number of runs up or down:	8.00000
Expected number of runs:	8.20000	Expected number of runs:	9.66667
Longest run about median:	3.00000	Longest run up or down:	3.00000
Approx P-Value for Clustering:	0.67293	Approx P-Value for Trends:	0.13819
Approx P-Value for Mixtures:	0.32707	Approx P-Value for Oscillation:	0.86181

Figure 4: Run Chart

Capability Chart

Having established the target for gearbox noise reduction USL=130dB and using the MINITAB a so called 'Capability Chart can be generated (fig.5). This graph is very important: it shows that the gearbox manufacturer can reduce the noise emitted by his gearboxes using only production means.

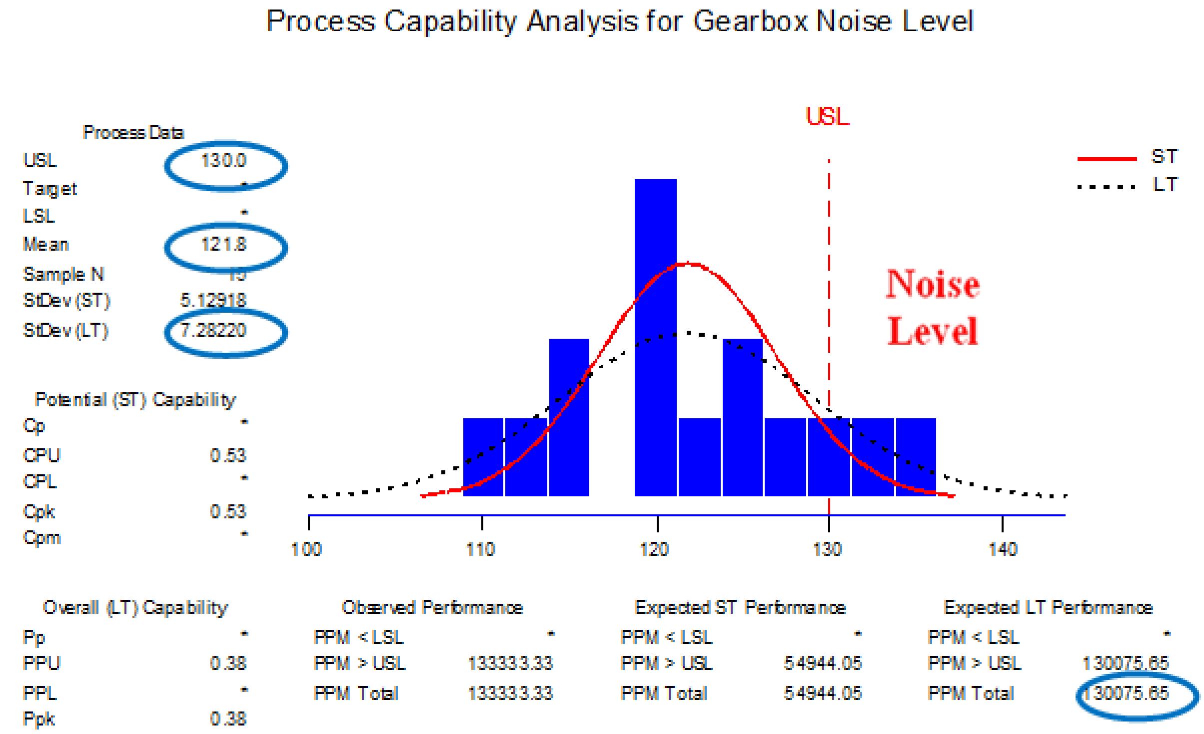


Figure 5: The capability chart

The Capability Chart is a strong instrument which gives important information on noise reduction potential. Noise reduction capability is related by the statistical notion called 'Standard

Deviation'. If n values are given for noise level $Y_1 \ldots Y_n$, then the average value $\bar{Y}$ ('Mean' in fig.5), is defined by:

$$\bar{Y} = \frac{\sum_{i=1}^{n} Y_n}{n} \qquad (1)$$

The Standard Deviation (s=StDev (LT) in fig.5) is given by:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} (Y_i - \bar{Y})^2}{n-1}} \qquad (2)$$

Looking on Capability Chart one can see that for the established USL=130 dB, the average level was $\bar{Y} = 121{,}8\text{dB}$ and the standard deviation (σ) for 'long term' identified in the above graph as StDev(LT) =7.2822. Thus, he can conclude that the 'sigma level of process' symbolized by Σ is defined by:

$$\Sigma = \frac{USL - \bar{Y}}{\sigma} = \frac{130 - 121.8}{7.2822} = 1.126 \qquad (3)$$

The value ∑=1.126 is called 'the sigma level of process' called in this example 'the noise generated by gearbox assembly'. The sigma level is important because shows to gearbox manufacturer that there is a room for improvement from the point of view of statistics. This will be a reference value for future improvements. When improvements will be applied on gearbox, the level of generated noise will decrease and the sigma level, ∑ correspondingly increases.
In fig.5, the value PPM (parts per million) =130075.65 extrapolates the present situation for 1 million of gearboxes showing that if 1 million of gearboxes will be manufactured. From 1 million manufactured gearboxes, 130075.65 gearboxes statistically will have the level of generated noise over 130 dB. The value P=PPM/1000 000=0.13007565 is the probability to have gearboxes with noise level over 130 dB.

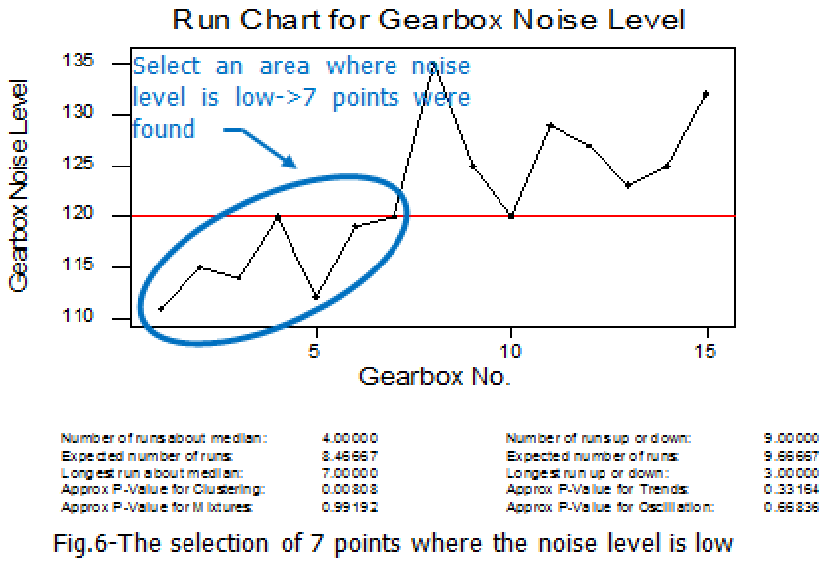


Figure 6: The selection of 7 points where the noise level is low

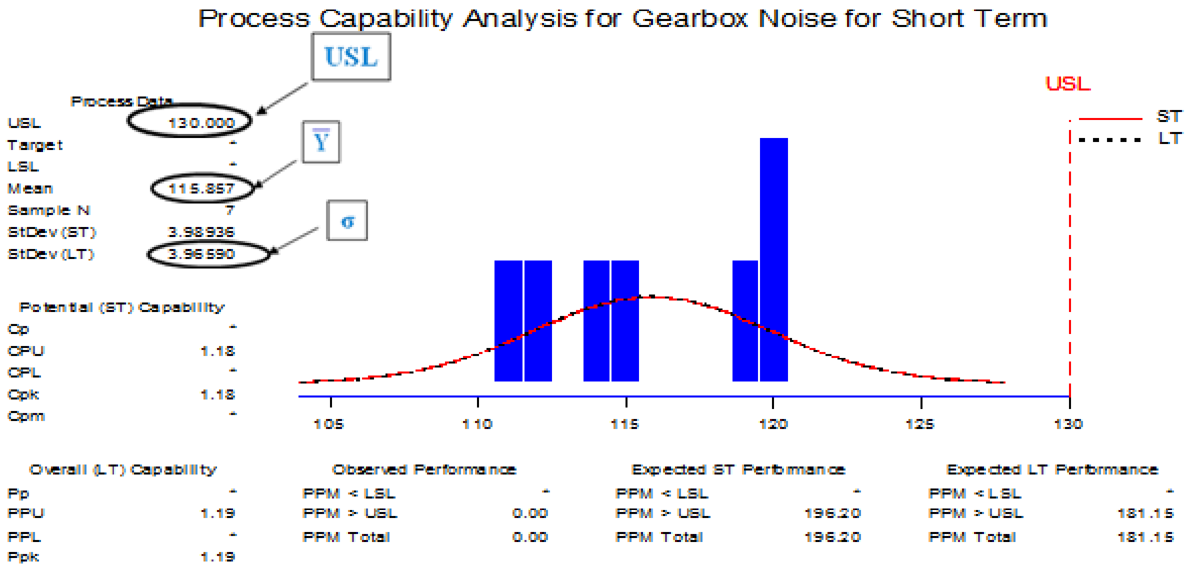


Figure 7: The capability for short term

Looking in fig.6, one can see that in 7 cases the noise emitted by gearboxes is much lower, under 120 dB. This shows a technological potential which must be closely investigated.
The Capability Chart done with MINITAB for the 7 selected points for the USL=130dB is presented in fig.7. In this graph one can see that the potential for noise level reduction inside the existing manufacturing process of gearbox is great. This fact is very important because shows that the

gearbox manufacturer could produce more silent gearboxes if the specific manufacturing conditions for the seven gearboxes are known. One can see that for the group of 7 parts, when USL=130 dB, Mean is $\bar{Y}$ = 115.857 dB and standard deviation is σ=3.9659. The sigma level of process for the case of short term, Σ_{ST} is:

$$\Sigma_{ST} = \frac{USL - \bar{Y}}{\sigma} = \frac{130 - 115.857}{3.9659} = 3.566 \tag{4}$$

The difference Σ_{ST} - Σ=3.566-1.126=2.44 is a measure of capacity to reduce noise level from the point of view of statistics. The value of PPM is now PPM=181.15. This value shows that if the manufacturer will make the gearboxes in the conditions of the 7 pieces, statistically only 181.15 gearboxes of 1 million will be generate a noise which is over the USL=130 dB. The potential probability to have gearboxes with noise level over USL=130 dB is P_{ST}=PPM/1 000 000 = 0.00018115.
At this point, the objective of manufacturer is be to find which the particular manufacturing conditions for the 7 gearboxes were in order to extend those conditions for all gearboxes that will be manufactured. In finding of those manufacturing conditions, using of Six-Sigma methodology will be useful too.

Step3-Finding the most significant factors through multiple linear regression

In the Step no. 1, 6 factors X_i which could influence the noise generated by gearbox were identified. For the 7 gearboxes having noise Y [dB] less than 120 dB, the measured dimensions registered on manufacturing sheets are according to Table 1 (for simplicity average values were calculated and used in MINITAB):

Table 1-Factor's values

Gearbox No.	X1	X2	X3	X4	X5	X6	Y
1	0.12	6.5	2.5	36	1.8	0.017	111
2	0.15	7.8	3.5	39	2.1	0.007	115
3	0.13	6.9	2.7	37	2.0	0.015	114
4	0.11	7.6	3.8	40	2.4	0.007	120
5	0.14	7.5	3.2	40	2.1	0.01	112
6	0.2	8.3	4.2	43	2.8	0.001	119
7	0.19	8.1	3.9	42	2.6	0.003	120

where the significance of X_i factors are given in fig.2.
Using these data in MINITAB, a Multiple Linear Regression can be generated (fig.8). This instrument is maybe the most important one because permits calculation of noise level Y function by the factors X_i. Although the regression formula is linear, it describes pretty well the mentioned dependence.
In fig.7, the parameter p* is a probability calculated for all the factors X_i. It represents the risk that X_i <u>to be not</u> a significant factor for noise level, Y. The lowest risk is for the factor X_2-Profile error of teeth. For this factor, p*=0.004, i.e. the probability as X_1 to have a strong influence on the noise level Y is equally to (1-0.004) =0.996=99.6% (a great value). This shows that the manufacturing people must focus on this factor, i.e. for example, to impose a smaller error for tooth profile and to buy a new grinding machine which can achieve this precision.
Other factors which could have a secondary importance are X_3 because p*=0.088, X_1 because p*=0.01 and X_4 because p*=0.037.
Action on production factors involves expenses and risks because, while p* has a higher value, the confidence that the appropriate X_i is really important factor for noise level decreases. For the factor X_5, p*=0.601 and for X_6, p*=0.975. The probability as X_6 (interference) and X_5 (roughness) to be significant for noise level Y is very small and they do not deserve a special attention.

Multiple Linear Regression

$$Y = -121 - 123\,X_1 + 27.8\,X_2 - 13.7\,X_3 + 2.11\,X_4 + 2.17\,X_5 - 27\,X_6$$

Predictor	Coef	StDev	T	P*
Constant	-120.71	44.42	-2.72	0.073
X1	-123.14	24.93	-4.94	0.016
X2	27.763	3.317	8.37	0.004
X3	-13.739	5.496	-2.50	0.088
X4	2.1112	0.5905	3.58	0.037
X5	2.172	3.729	0.58	0.601
X6	-26.8	781.0	-0.03	0.975

S = 0.7533   R-Sq = 99.8%   R-Sq(adj) = 99.5%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	6	956.30	159.38	280.84	0.000
Residual Error	3	1.70	0.57		
Total	9	958.00			

Source	DF	Seq SS
X1	1	504.44
X2	1	428.55
X3	1	5.68
X4	1	17.43
X5	1	0.19
X6	1	0.00

Figure 8: Multiple linear regression

4. CONCLUSIONS

▪Six-Sigma methodology currently used by aerospace companies for improving of product performances can be applied on noise reduction of complex assemblies, too.
▪The specialists in Six-Sigma can be used for noise reduction of complex assemblies together with specialists in aeroacoustics.
▪Using of Six-Sigma for noise reduction of complex assemblies which are currently in manufacturing can generate surprising solutions which can complete the solutions found by aeroacoustics.
▪Six sigma is a complex methodology which needs dedicated team of specialists to apply it. These specialists are working with the great aerospace manufacturers for improving of quality of current production and the can be used for reduction of level of noise generated by complex assemblies.
▪The instruments of currently applied Six-Sigma are much more numerous than those which were presented in this paper. The authors presented only several for understanding of principles.

REFERENCES

1. Asefeso, A.; 2012; Design for Six Sigma, AA Global Sourcing Ltd., 2012;

2. Eckes, G.; 2001;The Six Sigma Revolution-How General Electric and Others Turned Process Into Profits, John Wiley & Sons, Inc, 2001;

3. Maciejczyk, A., Zdziennicki, Z., Design Basic of Industrial Gear Boxes, http://cybra.lodz.pl/Content/3714/DesignBasicInd.pdf

4. Douglas C. Montgomery, Scott M. Kowalski; 2012; Minitab Manual Design and Analysis of Experiments, Wiley, April 17th 2012.