

NEW DIGITAL SIGNAL-PROCESSING APPROACH FOR TRANSMITTER MEASUREMENTS IN DVB-C SYSTEMS

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Abstract – An innovative digital signal-processing method, aimed at testing and troubleshooting QAM (Quadrature Amplitude Modulation) transmitters used in DVB-C (Digital Video Broadcasting-Cable) systems, is presented and validated. It takes advantage of a suitable clustering procedure, which is capable of recognizing the distorted pattern of symbols, produced by the transmitter under test, even when different impairments disturb, at the same time, the standard functioning of the transmitter itself. Right identification of the impairments along with accurate evaluation of their amount is then achieved through the application of original and straightforward measurement algorithms to the aforementioned pattern, properly corrected.

The results of a number of experiments, conducted on emulated QAM signals, show the superior effectiveness and reliability of the proposed method with respect to those assured by the measurement techniques suggested by ETSI (European Telecommunications Standard Institute).

Keywords: Transmitter measurements, Troubleshooting, I/Q impairments, QAM, Clustering.

1. INTRODUCTION

Use of telecommunication systems is becoming more and more widespread. The reason of this success lies essentially in the reduction of their cost, which is a consequence both of the recent progress in information technology and the growing business of telecommunication services. The most attractive and fashionable services offered to the user, such as digital video broadcasting (DVB), broadband internet, and so on, need the transmission of large streams of digital data in a very short time; this goal is achieved through sharp and somewhat puzzling digital modulation techniques.

Digital modulations have to be implemented by means of highly reliable equipment in order to (i) achieve the best performance in terms of occupied bandwidth, which is a very precious resource, (ii) satisfy EMC (ElectroMagnetic Compatibility) standards' requirements, and (iii) offer the requested quality of service. Performance assessment of terminal equipment is, therefore, a primary concern during

production, installation and maintenance stages, and it involves the current effort of numerous research groups in establishing suitable testing and troubleshooting techniques.

In the paper, a new measurement method for testing and troubleshooting QAM transmitters adopted in DVB-C systems is presented. The method goes beyond the partial and simplified approach given in ETSI measurement guidelines devoted to DVB-C systems (Technical report 101 290) [1] [2]. As a matter of fact, these guidelines do not provide any rule for associating the received symbols to their ideal position, even though this is a fundamental step for evaluating the effect of potential impairments. Moreover, most measurement procedures suggested by the guidelines work properly only in the presence of a single impairment at a time. The authors, instead, propose the use of (i) a suitable clustering procedure, mandated to the correction of the distorted pattern of received symbols, and (ii) original measurement algorithms, which face the problem of separating the effects of different impairments acting at the same time (a much more realistic situation), in order to proceed to an accurate evaluation of their amount.

2. IMPAIRMENTS AFFECTING QAM TRANSMITTERS

2.1. Preliminary considerations

QAM transmitters first modulate two baseband components (I and Q), the amplitude of which can assume only values belonging to a discrete set, with two in-quadrature sinusoidal signals, and then provide, at the output, the sum of the modulation results. In general, an M-QAM modulator accounts for a set of M symbols, which are represented by a specific pattern on a bidimensional space, namely the I/Q plane. For the sake of clarity, the pattern of a 64-QAM modulator is shown in Fig. 1; a decision boundary box can be associated to each symbol. In the presence of impairments and/or noise, which may deviates the actual position of transmitted symbols from their nominal positions, the QAM receiver decides for the transmitted value on the basis of the box that encloses the received symbol. The received symbol should be comprised within the appropriate decision box in order to avoid wrong decisions.

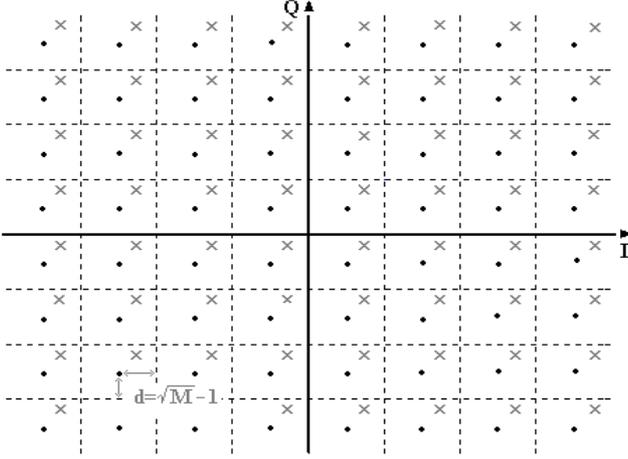


Fig.1 Effect of I/Q offsets on the pattern of transmitted symbols. The crosses represent the actual position of the symbols, while the dots their ideal ones.

2.2. Most common impairments

The performance of QAM systems is greatly influenced by the impairments that can affect QAM transmitters. In particular, the impairments that largely affect the probability of error in symbol recognition are generally classified on the basis of their effects on the I/Q plane (I/Q impairments). The most common of them are: *I/Q offsets* (c_1, c_2), *amplitude imbalance* (A), and *quadrature error* (ϕ).

➤ I/Q offsets move the origin of the pattern in a point different from the origin O of I/Q plane. Let the transmitted signal be represented by

$$y(t) = I(t) \cos(\omega_c t) - Q(t) \sin(\omega_c t) \quad (1)$$

in which ω_c is the carrier frequency and $I(t)$ and $Q(t)$ are respectively the levels of the in-phase and quadrature components.

The signal affected by I/Q offsets, c_1 and c_2 , can be represented by

$$y_{off}(t) = [c_1 + I(t)] \cos(\omega_c t) - [c_2 + Q(t)] \sin(\omega_c t) \quad (2)$$

Fig. 1 shows the effect of I/Q offsets on the pattern of transmitted symbols. The crosses represent the actual position, while the dots their ideal ones. As it can be easily verified for a M-QAM modulator, whose I and Q components are characterized by unitary maximum value, the requirements for a correct decision in the presence of only I/Q offsets are:

$$\begin{cases} |c_1| \leq \frac{1}{\sqrt{M}-1} \\ |c_2| \leq \frac{1}{\sqrt{M}-1} \end{cases} \quad (3)$$

➤ The amplitude imbalance, A , produces an asymmetrical pattern along the two coordinates, as it is shown in Fig. 2. The signal affected by amplitude imbalance can be represented by

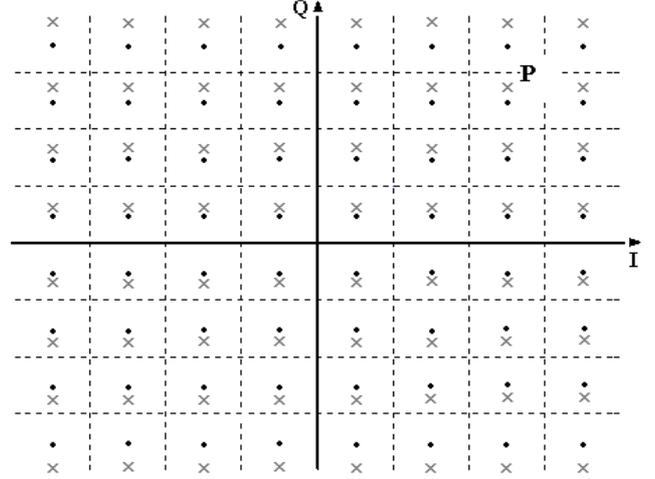


Fig.2 Amplitude imbalance produces an asymmetrical pattern along the two coordinates.

$$y_A(t) = I(t) \cos(\omega_c t) - (1+A)Q(t) \sin(\omega_c t) \quad (4)$$

It can be shown that the maximum tolerable value of A , established when noise and other impairments are absent, is

$$|A| < \frac{1}{\sqrt{M}-3} \quad (5)$$

It can be evaluated by referring to the points of the I/Q plane that are the most sensitive to this impairment; these points are the first to go off their appropriate decision boxes (as an example, point P in Fig. 2).

➤ *Quadrature Error* ϕ , reveals an angle different from 90 degrees between the two components I and Q. The signal affected by this impairment can be represented by

$$y_\phi(t) = [I(t) - Q(t) \sin \phi] \cos(\omega_c t) - Q(t) \cos \phi \sin(\omega_c t) \quad (6)$$

Fig. 3 shows the effect of the quadrature error on the pattern of transmitted symbols. With regard to the most sensitive points to this impairment, (as an example, point P in Fig. 3)

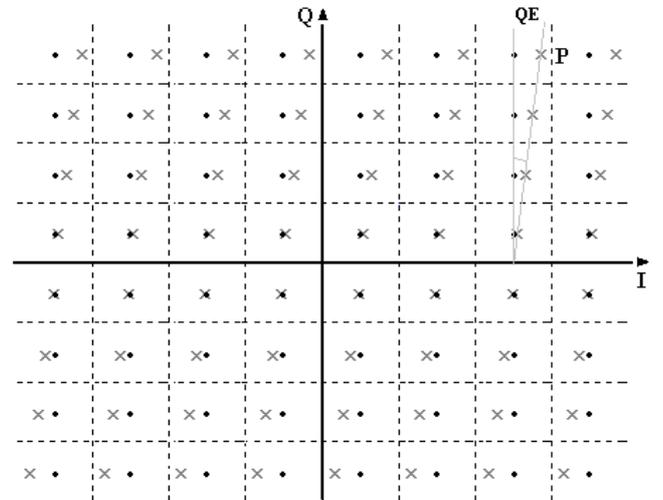


Fig.3 Effect of quadrature error on the pattern of transmitted symbols.

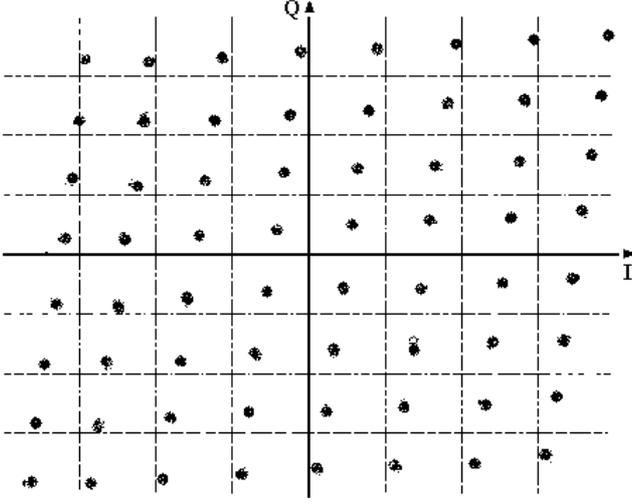


Fig. 4. Pattern of a QAM signal simultaneously affected by offsets, amplitude imbalance and quadrature error.

it can be shown that a wrong decision is avoided if the following relation is satisfied:

$$\phi < \frac{1}{\sqrt{M-1}} \frac{180}{\pi} \quad (7)$$

2.3. Final considerations

If the three impairments described above are simultaneously present, the received signal is

$$y(t) = [c_1 + c_2(1+A) \sin \phi + I(t) + (1+A) \sin \phi Q(t)] \cos(\omega_c t) + [-c_2(1+A) \cos \phi + (1+A) \cos \phi Q(t)] \sin(\omega_c t) \quad (8)$$

Fig. 4 shows the pattern of symbols produced by a QAM transmitter, simultaneously affected by offsets, amplitude imbalance and quadrature error. Moreover, it also accounts for little noise that spoils the demodulated symbols. The actual position of symbols is represented, in fact, by a group of points corresponding to different occurrences of the same symbol. It is worth noting that (i) the considered impairments can cause wrong decisions, and (ii) the contemporaneous presence of different impairments reduces the maximum tolerable amounts given in (3), (5), and (7).

3. PROPOSED METHOD

3.1. Signal Demodulation

In order to recognize the actual I/Q pattern characterizing the transmitter under test, the radio-frequency QAM signal is suitably digitised and demodulated by means respectively of a data acquisition system and suitable digital signal processing techniques.

The demodulation stage is intended to recover, on the I/Q plane, the actual position of symbols produced by the transmitter under test. To this aim, the receiver proposed by J.C.Song, H.J.Choi and K.Y.Kim in [4], which gains symbol timing recovery and phase synchronization through a DPLL (Digital Phase Locked Loop) based on a NDD (Non-Decision Direct) strategy is used.

3.2. Clustering procedure

Testing a QAM transmitter requires the observation of a number of symbols, N , much greater than the set of symbols, M , peculiar to the transmitter. The N collected symbols are grouped into M clusters by means of a suitable clustering procedure [5]. This procedure, at first, determines the pairwise distance between all the N observations, $d(i,j)$, and stores the results in a vector Y , named similarity vector. The $N(N-1)/2$ elements in the vector Y are suitably sorted according to:

$$Y = [d(1,2), d(1,3), \dots, d(1,N), d(2,3), \dots, d(N-1,N)] \quad (9)$$

in which the distance between the points i and j ($i < j$) is the element

$$d(i,j) = Y[(i-1)(N-i/2)+j-i] \quad (10)$$

Y is, then, passed to a *single linkage* algorithm that computes the hierarchical cluster information and returns the results in a matrix Z made up of $(N-1)$ rows and 3 columns. In particular, at the first step all the points observed are considered singleton clusters. At the generic step, i , the linkage procedure finds the two nearest clusters and merges them into a single cluster; the indexes of the clusters which have been combined are assigned to, respectively, the first and the second column of the i^{th} row of the matrix Z , while the distance between them is given in the third column. Index $N+i$ is assigned to the new cluster attained at the i^{th} step of the linkage procedure. If the newly formed cluster shows up in a latter row, that means it is being combined again into some bigger cluster. The results operated by the linkage procedure are clearly shown by the dendrogram plot of Fig. 5. The height of each upsidedown U shape line is the distance between the two clusters connected at that time. The matrix Z represents a hierarchical tree by which the N observations are easily grouped into M clusters.

3.3. Centroid algorithm

To evaluate the impairments presented in Section 2, for each cluster a single representative point, (I^k, Q^k) , $k=1, \dots, M$, is chosen according to the *centroid* algorithm,

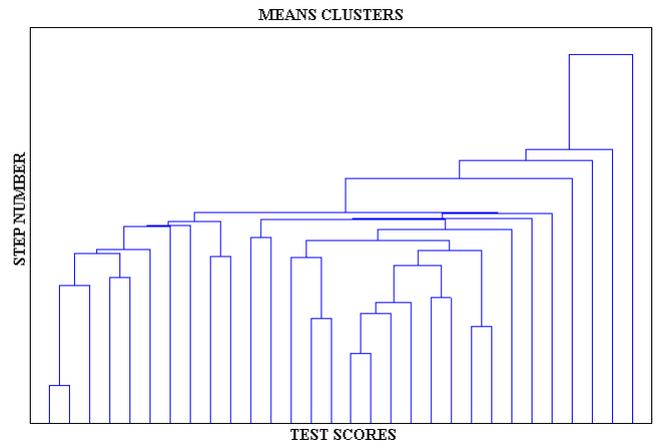


Fig.5 A dendrogram consists of many upsidedown U shape lines connecting nodes in a hierarchical tree. The height of each U is the distance between the two clusters to be connected at that time.

which gives the coordinates (I_r^k, Q_r^k) of the point characterized by the minimum value of the average distance from all the other points in the cluster.

Specifically, the representative points (I_r^k, Q_r^k) , $k=1 \dots M$, are determined by imposing

$$\min \frac{1}{N_k} \sum_{j=1}^{N_k} \left[(I_j^k - I_r^k)^2 + (Q_j^k - Q_r^k)^2 \right] \quad , \quad (11)$$

in which N_k is the number of points in the generic cluster k . Relation (11) requires to solve the equations

$$\frac{\partial}{\partial I_r^k} \left\{ \frac{1}{N_k} \sum_{j=1}^{N_k} \left[(I_j^k - I_r^k)^2 + (Q_j^k - Q_r^k)^2 \right] \right\} = 0 \quad (12)$$

and

$$\frac{\partial}{\partial Q_r^k} \left\{ \frac{1}{N_k} \sum_{j=1}^{N_k} \left[(I_j^k - I_r^k)^2 + (Q_j^k - Q_r^k)^2 \right] \right\} = 0 \quad (13)$$

whose solutions are:

$$I_r^k = \frac{1}{N_k} \sum_{j=1}^{N_k} I_j^k \quad (14)$$

$$Q_r^k = \frac{1}{N_k} \sum_{j=1}^{N_k} Q_j^k \quad (15)$$

3.4. Impairment evaluation

The evaluation of all impairments uses the representative points (I_r^k, Q_r^k) , $k=1, \dots, M$. In detail, the measurement procedure, first, requires the computation of the barycentre, (O_I, O_Q) of the set of M points (I_r^k, Q_r^k) , $k=1, \dots, M$. Then, using (8) it derives the following equations:

$$O_I = c_1 + c_2(1+A) \sin \phi \quad ; \quad (16)$$

$$O_Q = c_2(1+A) \cos \phi \quad , \quad (17)$$

Substituting in (8) the ideal coordinates (I_n^k, Q_n^k) , $n=1, \dots, M$, of each symbol, and taking into account (16) and (17), the following equations are achieved:

$$(1+A) \sin \phi Q_n^k = I_r^k - O_I - I_n^k, \quad k=1, \dots, M \quad ; \quad (18)$$

$$(1+A) \cos \phi Q_n^k = Q_r^k - O_Q, \quad k=1, \dots, M \quad . \quad (19)$$

In order to solve the system of $2M$ equations composed by (18) and (19), an estimate of the angle ϕ is determined by evaluating the average value of the incremental ratio along the Q coordinate of the points (I_r^k, Q_r^k) . The estimated value is substituted in (18) and (19), which are then solved by imposing the minimum average squared error in the estimate of A .

Finally, c_1 and c_2 , are evaluated according to

$$c_1 = OI - OQ \tan \phi \quad , \quad (20)$$

and

$$c_2 = \frac{OQ}{(1+A) \cos \phi} \quad . \quad (21)$$

which are derived by (16) and (17).

4. METHOD VALIDATION

4.1. Numerical tests

Several numerical tests have been carried out in order to optimise the algorithms used to evaluate the impairments. To obtain results independent from the particular stream of bits, the tests have been repeated many times on different pseudo-random sequences of bits.

The simulated signals, characterized by known impairments are first demodulated and then passed to the clustering procedure that evaluates the amount of the impairments by solving the equations described in Section 3.4. For a given set-up of impairments, about one hundred pseudo-random realizations have been considered in order to carry out a statistical analysis.

In particular, for a first set of simulations a single impairment has been considered. For a second set, two simultaneous impairments have been imposed to the synthesized signal. These tests are aimed at analysing the influence of an interfering impairment when the measurement of the other impairment is addressed. The last case is focused on the most general situation in which all the possible impairments are present.

A number of different situations have been considered in which the influence of an assigned couple of impairments on the other two has been analysed. Table I and the 3D histograms given in Fig. 7 provide an example of the results

Table I. Results of numerical tests on QAM signals characterized by different combination of impairments.

Imposed impairments				Evaluated impairments							
A	ϕ [rad]	c_1	c_2	A	ϕ [rad]	c_1	c_2	σ_A	σ_ϕ	σ_{c1}	σ_{c2}
0,1000	0,0654	0,0500	0,0000	0,0996	0,0646	0,0500	0,0002	0,0014	0,0009	0,0002	0,0012
0,1000	0,0872	0,0500	0,0000	0,0996	0,0864	0,0499	0,0000	0,0016	0,0015	0,0004	0,0014
0,1000	0,1309	0,0500	0,0000	0,0997	0,1300	0,0500	0,0000	0,0010	0,0019	0,0001	0,0013
0,3000	0,0654	0,0500	0,0000	0,2998	0,0647	0,0500	0,0001	0,0039	0,0011	0,0005	0,0013
0,3000	0,0872	0,0500	0,0000	0,2999	0,0867	0,0500	-0,0001	0,0034	0,0011	0,0001	0,0011
0,3000	0,1309	0,0500	0,0000	0,2998	0,1296	0,0500	-0,0001	0,0056	0,0021	0,0004	0,0011
0,5000	0,0654	0,0500	0,0000	0,4998	0,0650	0,0500	0,0003	0,0066	0,0010	0,0001	0,0012
0,5000	0,0872	0,0500	0,0000	0,4988	0,0864	0,0500	0,0000	0,0061	0,0011	0,0004	0,0011
0,5000	0,1309	0,0500	0,0000	0,4985	0,1301	0,0499	-0,0002	0,0042	0,0020	0,0003	0,0013

attained in the most general case. For each measured value (c_1 , c_2 , A and ϕ), its standard deviation is also shown (respectively σ_{c_1} , σ_{c_2} , σ_A , σ_ϕ) in Table I. The results of the numerical tests, both in terms of bias and standard deviation, are very satisfying if compared to those attainable from instruments currently available on the market.

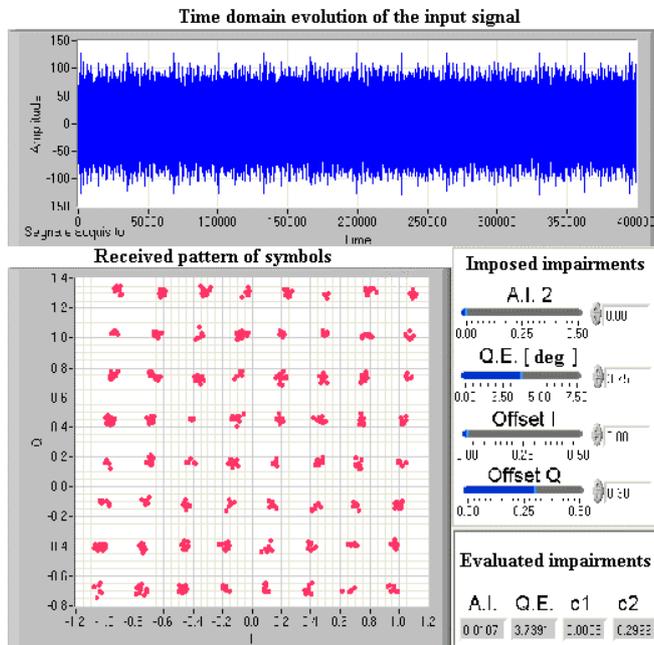


Fig.6 Virtual control panel of the automatic measurement station used to carry out the experimental tests on the emulated signals

4.2. Experimental tests

Many experimental tests have been carried out in order to validate the proposed method in the presence of actual signals digitised by means of an actual digitiser. A suitable automatic measurement station has been set up to achieve this purpose. The measurement station is made up of an arbitrary waveform generator (AWG), a digital storage oscilloscope (DSO) and a control and processing unit (PC), which are all interconnected by means of a standard IEEE interface bus. The signal digitally synthesized is transferred to the local memory of AWG and given in output in analogue form. DSO provides for the digitisation of the

analogue signal and passes the retrieved samples to the processing unit, which implements the proposed method.

Fig. 6 shows the virtual control panel designed to carry out the experimental tests. The virtual control panel highlights the time domain evolution of the input signal, and the actual pattern of symbols obtained by the demodulation stage.

Very critical signals, affected by great impairments, have shown the effectiveness of the clustering procedure introduced. In the presence of such a signal, the classical QAM receiver produces, in fact, error decision and, as a consequence, avoids the possibility of correct measurement. The proposed method is capable of attaining correct estimations of the imposed impairments even in these cases. The tests have been carried out producing in analogue form the same signals used in the simulations. The results corresponding to Table I and Fig. 7 are given respectively in Table II and Fig. 8. The comments reported in section 4.1 for the numerical tests are valid also for the results of the experimental tests, even though the standard deviation of the latter is slightly greater than that characterizing the numerical tests.

5. CONCLUSIONS

The paper has presented a method for the evaluation of the effect of the impairments affecting QAM transmitters in DVB-C systems. In particular, a suitable measurement algorithm aimed at estimating offset, amplitude imbalance and quadrature error has been developed, and validated through many experimental tests.

The main advantage of the method consists of its capability of matching the demodulated symbols to their ideal positions even when the combinations of all the impairments moves them outside of their own decision boxes. The proposed algorithms for the evaluation of the impairment have furnished good results if compared to those attainable from instruments currently available on the market.

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Table II Results of experimental tests in the presence of actual signals characterized by different combination of impairments.

Imposed impairments				Evaluated impairments							
A	ϕ [rad]	c_1	c_2	A	ϕ [rad]	c_1	c_2	σ_A	σ_ϕ	σ_{c_1}	σ_{c_2}
0,1000	0,0654	0,0500	0,0000	0,0969	0,0680	0,0507	-0,0001	0,0026	0,0057	0,0011	0,0012
0,1000	0,0872	0,0500	0,0000	0,0967	0,0892	0,0506	0,0000	0,0028	0,0073	0,0007	0,0014
0,1000	0,1309	0,0500	0,0000	0,0979	0,1351	0,0498	0,0001	0,0021	0,0110	0,0006	0,0011
0,3000	0,0654	0,0500	0,0000	0,2944	0,0639	0,0497	-0,0000	0,0057	0,0049	0,0007	0,0010
0,3000	0,0872	0,0500	0,0000	0,3063	0,0890	0,0502	-0,0000	0,0066	0,0065	0,0008	0,0011
0,3000	0,1309	0,0500	0,0000	0,2937	0,1278	0,0499	-0,0001	0,0055	0,0081	0,0010	0,0012
0,5000	0,0654	0,0500	0,0000	0,4935	0,0668	0,0500	0,0004	0,0078	0,0049	0,0013	0,0010
0,5000	0,0872	0,0500	0,0000	0,4927	0,0888	0,0499	0,0000	0,0068	0,0074	0,0004	0,0011
0,5000	0,1309	0,0500	0,0000	0,4989	0,1352	0,0500	0,0004	0,0077	0,0110	0,0007	0,0010

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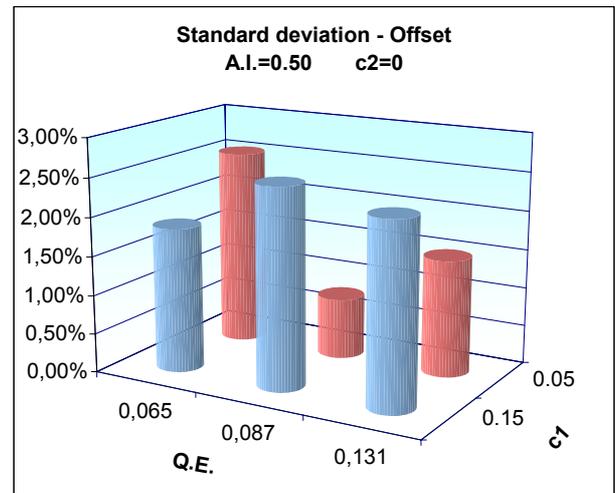
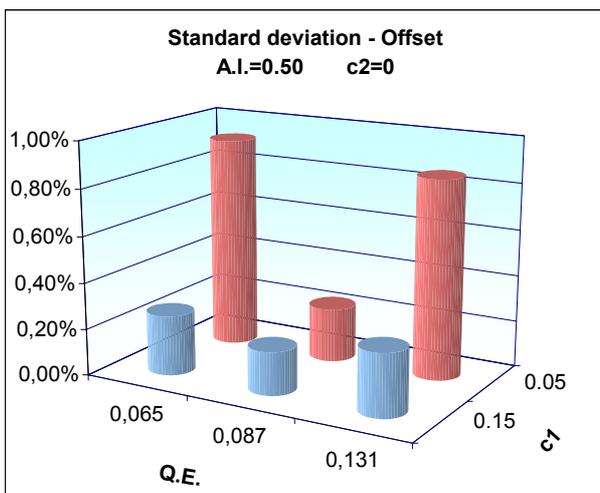
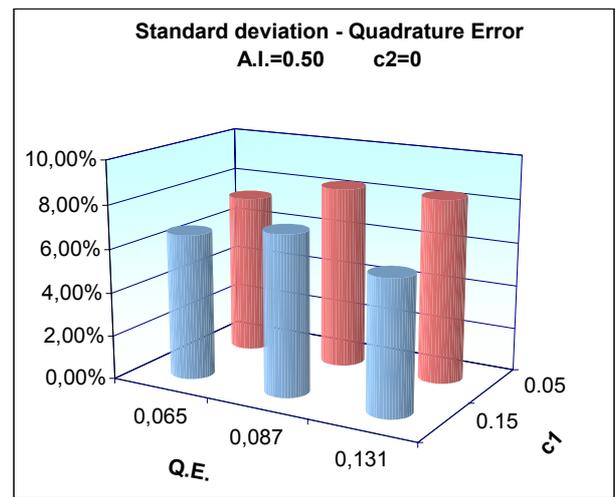
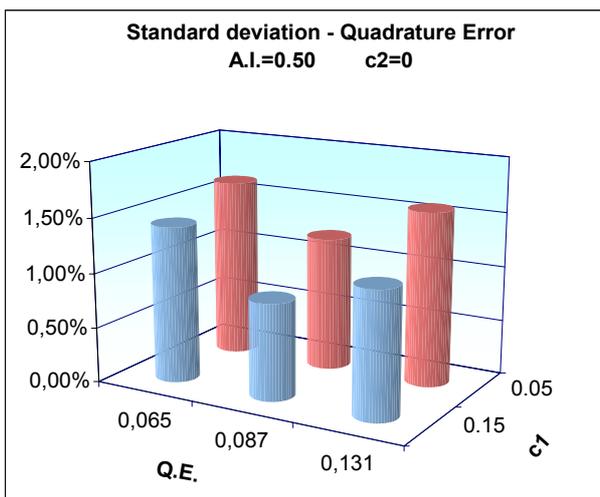
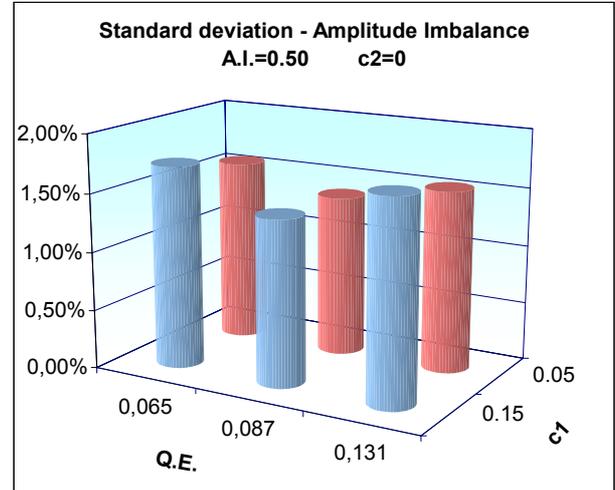
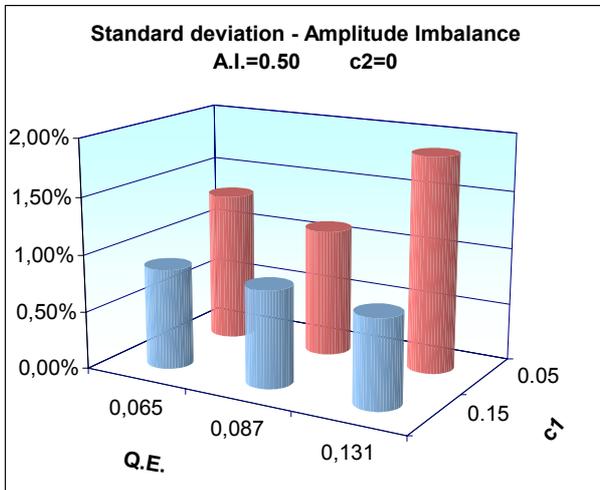


Fig.7 The 3-D histograms show the effect on the standard deviation of the numerical results related to a particular impairment due to the others.

Fig.8 The 3-D histograms show the effect on the standard deviation of the experimental results related to a particular impairment due to the others.