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Assessing the risk of designing a capacitor waveform recorder system using the FMEA method in order to reduce costs

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Abstract

The purpose of this research is to evaluate the design risk of the capacitive waveform recorder and extract the critical levels to prevent its occurrence in the waveform recorder. The simulated outputs were extracted using Proteus software in order to select the circuit with appropriate accuracy.
In this research, FMEA method is used to evaluate failure modes. All parts of the waveform recorder were evaluated and states, effects and causes of failure were calculated and evaluated. Then the risk number of each failure was calculated and its crisis level was prioritized.
The purpose of FMEA is to support decisions that reduce the probability of failures and their effects and help improve outputs.
FMEA documents can only include a brief statement of proposed exposures or design changes: replacing elements with more reliable one, introducing backup systems, and new or improved methods that limit damage. In conducting the research, the general process for FMEA evaluation was determined. Then, by interviewing experts in the field, the failure modes of the design of the capacitor waveform recorder were analyzed. Critical situations were extracted and countermeasures were suggested to improve performance. Two methods of simulation and interview were considered to collect information. The relationship between circuit design cost and design error analysis was extracted and it was observed that with the increase of DFMEA, in addition to increasing the number of parts and increasing the risk of failure, the cost of circuit design and construction and measurement error increases.

Keywords Design risk, capacitive waveform recorder, critical levels, risk number, error analysis

Introduction

Water resistance affects a moving float that is partially submerged in water. A part of the floating function is used to overcome friction, another part is used to form eddies in the water, liquid turbulence, and a significant part is used to form waves.
Floating heel waves can be recorded with an waveform recorder. It is very necessary to measure the wave parameters in the water channel.
Determining the parameters of the floating waves that appear due to the movement of the model is not a simple technical issue. In order to obtain reliable parameters in the measurement of waves, it is necessary to observe conditions. These conditions include the following states according to different issues:
1- Recording a large number of parameters, including height, length and period of waves, direction and speed of wave movement.

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2- Providing recording of waves in the frequency range from 0.01 Hz to 1 Hz and in the height range from 1 mm to 300 mm.
3- Provision of simultaneous operation of sensors in the multi-channel measurement system.
Measuring surface waves is similar to measuring the displacement of the water surface. Therefore, all water level measurement methods can be used to measure surface waves, taking into account the limitations mentioned above.
According to the conditions, different methods are used to measure surface waves. To measure the level of liquids at close distances, a visually graduated level gauge (graduated glass) is used.
Hydrostatic stations, floating buoys, capacitance, inductivity, conductivity, optical, radioisotope, radio waves, microwave, acoustic (ultrasonic) and other level gauges are used to measure the level of liquids at long distances.
In the technical design stage of the wave recorder system, the possible methods for measuring liquid levels, the basics of selecting the capacitance method and measurement methods have been taken into consideration, and the best approximation for measuring waves in a laboratory or water channel is the capacitance measurement method of surface waves.
The wave recorder system must have the ability to automatically collect information, digitize data related to wave parameters, and send them to a computer for storage and primary processing of information.
The system for measuring and recording wave parameters consists of the sub-system for measuring surface waves, communication cables and data conversion and input device. Each sub-system for measuring wave parameters includes wave sensors and data conversion and transmission devices. The information related to surface waves is entered into the computer and is displayed on the screen and stored in the computer's memory.
In the design of the wave measurement sensor, it takes place from the capacitance changes between two insulated wires with diameters of 0.6 to 1 mm, which are placed in parallel at a distance of 4 to 5 mm.
The methods of measuring very small capacitors (less than nanofarads) are different. The principles of operation of these methods, such as the use of dual differential circuits, RC phase delay (charge and discharge), oscillator, capacitor to phase angle converter, have been investigated. Measurement range, sensitivity, percentage of error and application are important and main measurement parameters.
To measure the range of waves from 1 mm to 300 mm, we need a circuit that can measure capacitors from 0.1 to 50 picofarad. According to the investigations carried out in the above article, the double differential method and the charging and discharging method can be used in this range.

Research Methods

The research method is an applied and developmental research. Optimizing the waveguide, designing and building it with improved methods, reviewing and changing existing design methods and reducing costs are the main goals of this research. This is done by analyzing failure modes.
The type of research is from the point of view of data and quantitative-qualitative analysis method. First, we extract the parameters, then we collect the necessary data with the questionnaire and other tools such as simulation soaftware, the variables are measured, and finally we find the relationships between them.
The research method is based on the method of control over research and descriptive data and is used through interviews, observations and questionnaires to understand the effects of failure in the design of the wave recorder and reduce the cost of the design.
The research method in applied engineering studies is quantitative.
The method of collecting information is library (reading text, reading statistics, using database, reading images, using maps, reading documents) and field (observation, interview, test, questionnaire, audio and video).

Working method of the wave amplitude sensor
All over the world, a capacitor system with varnished wires is usually used to make a wave recorder. In order to make such a system, you must first make its capacitor part. To make the desired capacitor, we fix two covered copper wires with a diameter of one millimeter and a length of one meter on a support rod in such a way that there is no electrical connection between the plates of the capacitor and the support rod.
Waves enter the waveform recorder from all sides, so the waveform recorder wires must be arranged in such a way that the wave passes through it the same way. For this reason, thin circular and coated wires are used so that the wave direction does not affect the effective cross-sectional area. The end part of the metal wires that are placed in the water must be completely sealed so that if the electrical conductivity of the water is high, it will not cause the connection of the capacitor plates. This capacitor depends on the transmittance coefficient of the water in which the measurement is performed, so in the first step of placing this capacitor in any water for measurement, it must be calibrated first.
Capacitance relationship for flat capacitor is as follows:

$$c = \frac{k\epsilon_0 A}{d}$$

where c is the capacitance of the planar capacitor in terms of farads, ϵ_0 is the vacuum permeability constant in terms of farads per meter, k is the dielectric coefficient of a dimensionless number, A is the area of the plates in square meters and d is the distance between the plates in meters. For the system in question, due to the fact that the water dielectric is between the plates, therefore, due to the changes in the height of the water between the plates caused by the waves created, the amount of this capacitor changes and by measuring these changes Calculate and measure the amplitude of the generated waves. Considering the relationship related to the capacitance and the fact that the dielectric constant is

$$k{=}78 \text{ and } \epsilon_0 = 8.85 \times 10^{-12}\,\frac{F}{m}$$

and the distance between the plates is 5 mm and the diameter of the wire is 1 mm, we have:

$$c = 1.38 \times 10^{-10} h$$

According to the above relationship, if we measure the capacitance of the plates, we can calculate h, which means the amplitude of the wave.
To show negative wave heights, two capacitor plates should be placed in the water so that half is in the water and half is out of the water. For this purpose, the circuit should be such that a negative number is displayed if the wave amplitude becomes negative, and a positive number is displayed if the wave amplitude is positive. So in practice there are two capacitors that are parallel to each other. The first capacitor is 69 picofarad (according to the relationship above and that 500 mm of it should be placed in water) and the second capacitor which is parallel with this capacitor and varies between 1 tenth of picofarad and 42 picofarad.
Therefore, a circuit is needed to measure the capacitance between 27.6 picofarad and 110.4 picofarad. Also, the program must be written in such a way that for a wave height of -300 mm (in this case, 200 mm of the capacitor is in the water), the lowest capacitance is 27.6 picofarad, and for a maximum wave height of 300 mm (in this case, 800 mm of the capacitor is located in the water) to show the maximum capacity of 110.4 picofarad.
Therefore, the block diagram of such a system is shown in Figure 1.

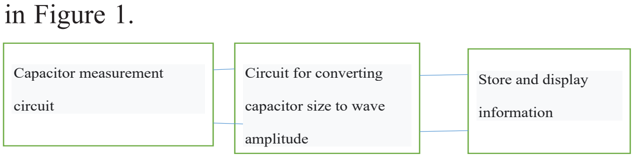

Figure 1 Block diagram of the waveform recorder system

Due to the fact that the length of the wires is chosen to be one meter, it is therefore possible to measure waves with a range from 1 mm to 300 mm. Amplitudes lower and higher than this value due to being close to the edges of the capacitor may not be linear and have insufficient accuracy.
Several sensors can be used to measure the periodicity of waves. The working method is that it is enough to measure the arrival time of one peak and one trough (high tide and low tide) or two peaks and calculate the periodicity according to that. This work can be done by the system or after measuring and recording the waves. If the time between a peak and a trough is measured (that is, when the capacitor has the highest capacity and the lowest capacity), this time can be measured as half the cycle period, and if the time between two peaks or two troughs is measured. (that is, the two states where the capacitor has the highest capacity), this time can be considered as a periodic period.
Making such a circuit is very simple and cheap. LCD display and Arduino are used to display the measured data.

Wave sensors

Wave sensors have primary converters and matching devices. The primary converter is of capacitor type and in order to convert the fluctuating level of water, it is the size of an electric capacitor. From the structural dimension, the primary converter has a system consisting of two insulated wires with a diameter of 1 mm, which are stretched parallel to each other at a distance of 5 mm on a stainless steel rod with a diameter of 8 mm. How to place the wires on the holder is shown in Figure 2. During the measurements of surface waves, the holding rod is placed vertically and half the length of the insulating wires is immersed in deep water during the measurement.

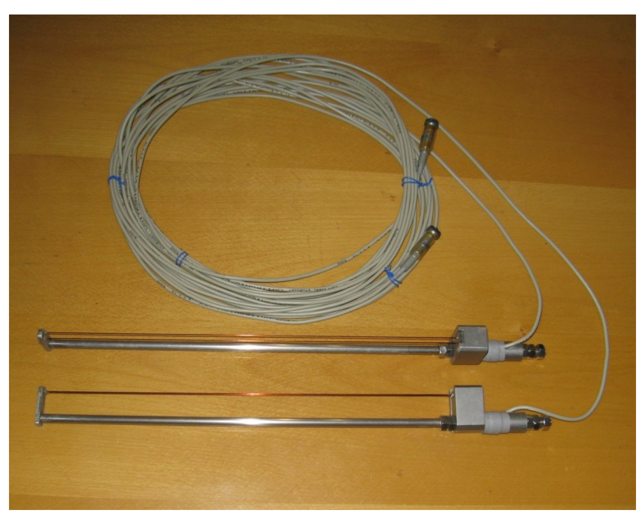

Figure 2 How to place the wires on the holder

The length of the measuring part of the wave sensor is determined according to the length of the insulated wires. According to the requirement in the water channel, the maximum measuring range of wave height is less than 300 mm. Due to the fact that there may be an error in the measurement at the end points of the sensor, therefore, the length of the insulated wires is 500 mm.

While measuring the surface waves, the wave sensors are placed vertically and immersed in water half the length of the insulated wire during the measurement in deep water. Before measuring, the wave sensors must be calibrated. For the purpose of calibration, we continuously and steadily submerge the wave sensors in water 10 mm by 10 mm in a period of time until the entire sensor is in the water. Pulling up the wave sensors is done in the same way. In the following, there is an abstract of system and design failure modes. Exposure measures required at each stage are suggested.

Table 1 Abstract of SFMEA for Waveform System

Except	Operation	Failure mode	Local Effect	Overall Effect	Severity	Occurrence	Detection Capability	RPN	Exposure Action
sensor	Creating a capacitance that fits the received waves	Sedimentation of the sensor and change of the calculation coefficient	Changing the thickness of sensor wires	The wave recorder does not display the wave amplitude correctly	4	6	5	120	Dry and clean the sensor after each measuring step
Capacitormeasurement circuit and conversion to wave amplitude	Converting the capacitance generated in the sensor to the wave amplitude number	Microcontroller circuit failure or communication cables	Some signals cannot enter the storage and display	The waveform recorder does not display the amplitude of some waves	7	3	2	42	Using micro-controllers and supporting cables
Data storage and display	Visual display and storage of the wave height created in the sensor	Lack of visual display of received waves and not saving the data of a sensor	Failure to display the range of waves or failure to save the data of a sensor	The frequency of received waves is not stored or displayed	4	4	3	48	Use different colors to display each signal

Table 2 Abstract of DFMEA for sonar system sensor

Except	Operation	Failure mode	Local Effect	Overall Effect	Severity	Occurrence	Detection Capability	RPN	Exposure Action	RPN after exposure action
Sensor wires	Converting wave kinetic energy into capacitance	Losing the lacquer shell, changing the distance between the wires	Capacitance change	Not working properly	4	5	4	80	Use of wires with a strong shell	48
Sensor wires	Converting wave kinetic energy into capacitance	Using capacitor plates instead of wire	Inability to measure waves at an angle to the wave generator	Not working properly	6	3	7	126	Use of coated wires	80
Sensor holder	Converting the capacitance generated in the sensor to the wave amplitude number	Stretching of the wires or improper placement of the wires between the holders	Capacitance change	Not working properly	4	5	5	100	Careful inspection of the holder before calibration	60
Sensor cable	Transmission of electrical signals caused by waves	Increasing the length of cables in long distance transmissions	Capacitance change	Not working properly	4	4	4	64	Using on-site measurement methods with a short cable or active measurement methods	32

Table 3 Abstract of DFMEA for electronic circuits of waveform recorder system

Except	Operation	Failure mode	Local Effect	Overall Effect	Severity	Occurrence	Detection Capability	RPN	Exposure Action	RPN after exposure action
capacitive bridge	Conversion of capacitor changes to voltage difference	One of the impedances does not work properly	Change the size of the capacitor	Not working properly	6	6	3	108	Using precision capacitors and military resistors	90
Amplifier	Increasing the measurement range	Failure to amplify the signal at the desired frequency	Change the size of the capacitor	Not working properly	4	5	3	60	Use of optimal amplifiers	60
Filter and rectifier	Removing unwanted signals and straightening the signal	No removal of unwanted signals and no rectification	Change the size of the capacitor	Not working properly	6	6	5	180	Using filters and active rectifiers	150
Collector	Sum of input signals	Failure to add signals	Change the size of the capacitor	Not working properly	6	3	4	72	Use of appropriate amplifiers	48
Wave height measurement and display circuit	Wave amplitude display and necessary conversions	No height display	Screen off	Not working properly	5	4	8	160	Use the appropriate display	80

Table 4 Abstract of the DFMEA for the capacitor-to-amplitude conversion circuit of the waveform recorder system

Except	Operation	Failure mode	Local Effect	Overall Effect	Severity	Occurrence	Detection Capability	RPN	Exposure Action	RPN after exposure action
Microcontroller	Generation of alternating voltage for capacitor bridge	No voltage generation	Failure to create a suitable differential voltage	Not working properly	6	5	5	150	Using industrial microcontroller or Arduino industrial boards	50
Microcontroller	Perform calculations to convert capacitance to wave amplitude	Miscalculations	Wrong domain display	Not working properly	6	4	6	144	Correcting programs and using Arduino industrial boards	60
Analog to digital converter	Converting generated voltages into binary numbers	Failure to convert to the appropriate voltage with the required accuracy	Wrong domain display	Not working properly	7	4	7	196	Using the internal converter	49
Serial port	Transferring information from the micro to the display	Failure to display correct information	Receive incorrect information	Not working properly	6	5	7	210	Using a parallel display	42
Serial port	Data transfer from micro to computer	Failure to display the correct height of the wave	Displaying incorrect data on the computer	Not working properly	5	4	2	40	Using the internal serial port	20
Display and storage	Display and save data	Failure to display or store data	No data display	Not working properly	6	4	4	96	Using a suitable display and additional external memory to store data	48

Due to the clarity of the error analysis results for the parts, the error analysis of the parts was not discussed in this article.

By using these tables, various errors are identified and by calculating the critical errors, the design is changed to create a suitable circuit with the desired error.

After changing the design, RPN was recalculated and in some cases the circuit design was changed to produce the output with proper accuracy. In this case, the outputs were extracted using Proteus software and compared with the previous cases. C software was used to program Arduino.

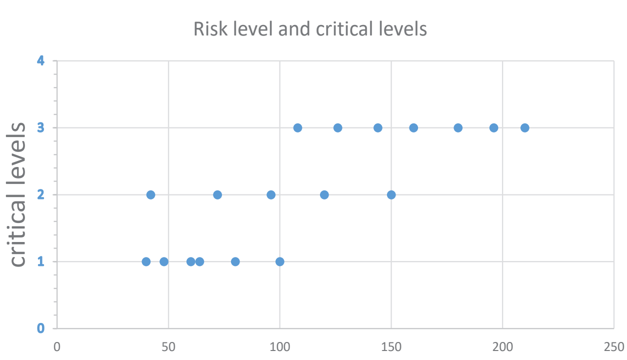

Figure 3 Risk criterion number according to critical levels

Determining the level of acceptable risk

In the method used in this research, the risk criterion number is used for the level of acceptable risk. The risk criterion is an indicator to separate the amount of acceptable and unacceptable risk.

An error whose RPN number is higher than the risk criterion is unacceptable, and if it is lower than the risk criterion, it will be acceptable. In order to determine the level of the risk criterion, a dot diagram is drawn for each component of the system based on the RPN number and the level of crisis of that component. According to the diagram, the first point that is placed at crisis level 3 is the risk measure for the system.

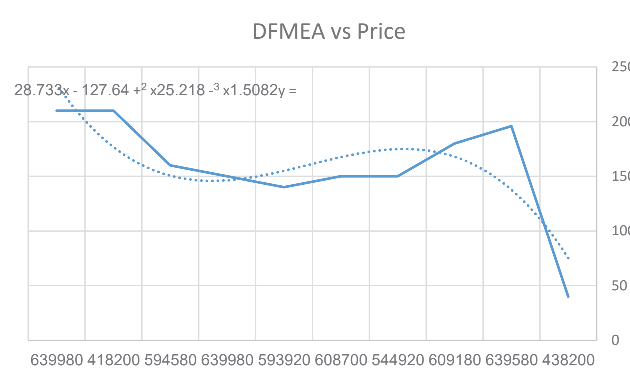

Figure 4 The graph shows that as the component price decreases, the DFMEA also decreases.

Cost and number of parts

Table 5. For each designed circuit, parts price, number of parts and maximum DFMEA were extracted.

Table 5. Parts price, number of parts and maximum DFMEA For each designed circuit

Circuit type	Number of parts used	Price	MAX of DFMEA	Measurement Error	Arduino	LCD	Opamp	R	C	Pot	Diode	Micro
					348000	75000	15000	110	90	15000	16000	193000
Charging and discharging with Arduino	5	438200	40	0.67%	1	1	0	1	1	1	0	
general circuit	40	639580	196	1.6%	1	1	9	21	3	1	4	
Circuit without differential amplifier	34	609180	180	2%	1	1	7	19	1	1	4	
Circuit without active rectifier	28	544920	150	3%	1	1	7	15	3	1	0	
Circuit without filter	30	608700	150	3%	1	1	7	13	3	1	4	
Circuit without adder	31	593920	140	3%	1	1	6	15	3	1	4	
Circuit with capacitor bridge	44	639980	150	2%	1	1	9	23	5	1	4	
Single differential amplifier circuit	35	594580	160	3%	1	1	6	21	3	1	4	
Charge and discharge circuit with microcontroller	5	418200	210	2%	0	1	0	1	1	1	0	1
oscillator	44	639980	210	2%	1	1	9	23	5	1	4	

Data Analysis

For data analysis, critical levels were considered as follows:

Level 1, normal level in which all three RPN number factors have a number less than 6, or the RPN number is low and the need for preventive measures is not felt.

Level 2, the semi-critical level in which at most one of the three factors of the RPN number has values higher than 6, but the RPN number is low. In this case, it is necessary to take preventive measures.

Level 3, the critical level in which at least two of the three factors of the RPN number have values higher than 6 and the RPN number is also high. It is clear that this level requires urgent preventive measures.

To determine the risk criterion number (acceptable level of risk) in this research, it has been done in such a way that after calculating the RPN for all subsystems, a dot diagram was drawn based on the two factors of the crisis level and the RPN number, which in this diagram in addition When the RPN numbers are specified, the number of errors in each level are also shown.

According to the diagram, the first point that is placed at level 3 specifies the risk criterion, where the number 108 is set as the boundary of acceptable and unacceptable risks.

Interpretation of results

18 basic design errors were analyzed. Of these, 9 errors were critical for which corrective measures were taken in the design and the number of errors was improved. 3 errors were semi-critical for which countermeasures were provided. Due to the failure to correct the error after face-to-face actions, in some of the errors, it was proposed to remove these circuits and use the internal circuits of the Arduino board. With this, in addition to reducing the risk, the cost of using additional parts is also eliminated. In this case, design errors are limited to programming errors and a sensor resistor and capacitor. In this case, failure analysis reduces the number of used parts and, in addition to circuit modification, reduces costs. Wave measurement circuits use techniques such as radar, laser or other methods. In the laboratory, according to the customer's needs, it is not cost-effective to use the above methods. It is customary to use capacitor measurement circuits in all sensors; But it is difficult to measure capacitors less than picofarad in the usual way. In all existing waveform recorders or capacitance measurements, the measurement range is 1 picofarad to 1 microfarad and larger, after these methods the expected output cannot be obtained. Common microcontroller methods have an error higher than 4 microseconds.

By using Arduino boards, the measurement error was 4 microseconds, and by changing the board, an error of less than a few nanoseconds can be expected, but the cost of the circuit design increases.

By using error analysis, appropriate sub-systems for the waveform recorder were designed, which, in addition to proper accuracy, have less environmental effects on it, and due to the reduction of parts, the cost has also been reduced. The results showed that the error analysis helps to improve the design and reduce the costs of parts of the circuit, and in some parts it may not have a significant effect.

Considering the problems of environmental effects and water type on wave measurement sensors in real environments outside the laboratory, it is suggested to investigate other methods in this field or to use high frequency Arduino boards in such environments.

Corrective actions and suggestions

According to the critical levels, the following corrective actions were taken:

1- Dry and clean the sensor after each measuring step.

2- Instead of parallel plates, coated wires were used to change the capacitance.

3- Instead of passive filter and rectifier, active filter and rectifier were used, and due to its low effect, the filter was removed and micro internal circuits were used to produce the appropriate pulse.

4- Due to the problems of series displays, a suitable parallel display was used. Due to the ability to connect Arduino boards to a computer, a computer can be used to display and store data.
5- Arduino industrial boards were used instead of microcontrollers. These boards have all the positive features of microcontrollers, and in addition, they have the necessary internal 8 or 16-bit converters.
6- The programs were corrected and Arduino boards were used instead of microcontrollers and additional interface circuits.
7- An internal analog to digital converter was used instead of an external converter.
8- The circuits of differential amplifier, filter and rectifier, analog to digital converter and adder circuit were removed in the final circuit.
9- A 28 megohm resistor was used, and according to the error of the Arduino board's time commands, which is 4 microseconds, the error of measuring the wave amplitude is 2 mm.
10- According to the measurement program, the Arduino board must measure every 2000 microseconds or in other words 2 milliseconds, and it is not possible to measure waves with a periodicity less than 10 times this time, i.e. 20 milliseconds.

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