# Real-Time health monitoring system for Trisonic Wind Tunnel Nozzle

Harikrishna Devisetty[1], Chennaiah M. P[2], D.B. Singh[3]
[1] PG Scholar, Electronics and Communication Engineering, GVIC Angallu, Andhrapradesh, India
[1] Technical Assistant, NTAF, CSIR-National Aerospace Laboratories, Bangalore, Karnataka, India
[2] Professor & HoD, Electronics and Communication Engineering, GVIC Angallu, Andhrapradesh, India
[3] Principal Scientist, NTAF, CSIR-National Aerospace Laboratories, Bangalore, Karnataka, India

## ABSTRACT

*The CSIR-NAL, National Trisonic Aerodynamic Facilities (NTAF) divisions, 1.2m*1.2m Trisonic wind tunnel is operated in Sub-sonic, Transonic and Supersonic Mach number testing (0.2-4.0). The Flexible Nozzle (FN) is the important component of the Trisonic wind tunnel. The nozzle is formed by a pair of flexible steel plates, set to form appropriate contour along the top and bottom of the flow channel. It is operated and controlled by hydraulic actuators located at 17 stations. The over-stress encountered on these plates due to faulty curvature (excessive bending) settings, or Malfunctioning of hydraulic jacks such as jamming of the actuating cylinders, or Curvature sensor problems. The curvature sensor assembly is mounted on flexible nozzle edge at different locations to identify the over stress. Due to Wind Tunnel test duration limit (around 30-40 seconds) and series connected sensors, it is highly challenging to identify the stress occurrence at the particular station by scanning through the selector switch. To overcome this Problem, real-time health monitoring system for flexible nozzle has been implemented in the 1.2m Trisonic Wind Tunnel. Here, the limit switch outputs are parallelly connected to NI based hardware. In case of the stress occurrence on the plates, it will be recorded and displayed in real-time software.*

**Keyword : -** *Flexible Nozzle, Mach number, Wind Tunnel, Trisonic, Sub-sonic, Transonic, Super-sonic*

---

## 1. INTRODUCTION

The NTAF division of CSIR-NAL has been serving the country as a core of research and development in high speed aerodynamics since the last five decades. The NTAF division is well known for its long and proven experience in providing high quality vital and strategic experimental aerodynamic data required for complex aerospace programmes of the country with the unique ability to develop novel and advanced test techniques. A wind tunnel is a tool used in aerodynamic research to study the effects of air moving past the solid object. The Wind tunnel works on the principle that a stationary model with air moving around it behaves the same way as in actual full-scale object under test moving through stationary air. The wind tunnel testing for small scale models is very important to evaluate the various characteristics of aerodynamics and it will be expensive too. Every wind tunnel test will be conducted very carefully and needs to give the accurate and qualitative data. The demand is increasing constantly for wind tunnel data accuracy follows naturally from the demand for improved full scale vehicle performance and accuracy of performance prediction. In Wind Tunnel testing of scaled down models at different mach numbers and contour settings for mach numbers will be done by using the flexible nozzle. The FN is the important component of the Trisonic wind tunnel. The FN geometry inimitably regulates supersonic and transonic Mach number for the wind tunnel testing. This paper, describes the 1.2m Trisonic wind tunnel FN health monitoring system developed by using the NI cDAQ-9136 & NI modules. The user interface with real-time data analysis capability implemented on a NI based computer system.

### 1.1 Classification of Wind Tunnel on the basis of speed

The Wind Tunnels are majorly classified as two types, closed loop and blowdown type. The Wind tunnels are often denoted by the speed of air in the test section relative to the speed of sound i.e. Mach number (M). The mach number is the ratio between true air speed of the aircraft and the local speed of sound. It is dimension less quantity. In the aerodynamics, the critical mach number will reaches the speed of sound at some point of the aircraft but it does not exceed above that. The Wind Tunnels are classified on the basis of mach number as, sub-sonic (M < 0.8 and speed <980 km/h), transonic (0.8 < M < 1.2 and speed 980-1470 km/h), super-sonic (1.2 < M < 5.0 and speed 1470-6126 km/h) and hypersonic (M > 5.0 and speed 6126-12251 km/h).

### 1.2 CSIR-NAL TRISONIC WIND TUNNEL (1.2m*1.2m)

The 1.2m Trisonic Wind tunnel is completed 50 years recently and giving significant contributions to the Indian nation in the field of aerospace to develop novel and advanced techniques. In 1.2m Trisonic Wind tunnel has efficient control system and data acquisition system to obtain the accurate and high quality aerodynamics data of the model and implemented various flow control techniques. The various sub-systems of the Trisonic wind tunnel are listed below and their description as follows;

i) High Pressure air storage vessel
ii) Butterfly/Shut-off Valve
iii) Pressure Regulating Valve
iv) Settling Chamber/Flow conditioner
v) Flexible Nozzle
vi) Model cart/Test Section
vii) Variable Diffuser

The Trisonic wind tunnel is Contributing to National programmes of CSIR-NAL, DRDO, ISRO and HAL. The schematic diagram of Trisonic wind tunnel and Integrated Tunnel control system is shown in figure 1.

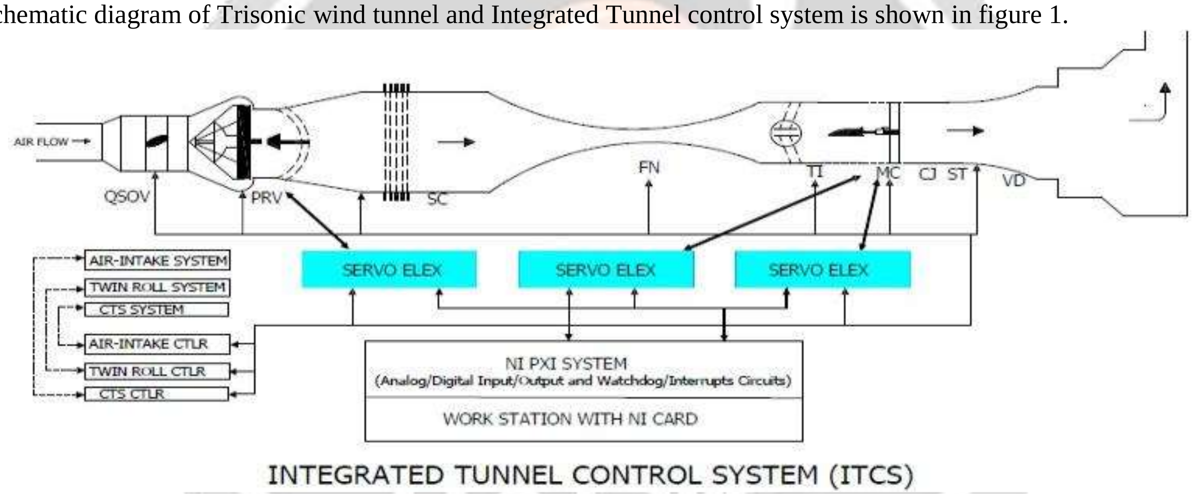



**Fig -1**: Schematic diagram of Trisonic wind tunnel (1.2m*1.2m) and ITCS

The compressor system is the main source for the supply of compressed air to the wind tunnels. The air storage system has a capacity of approximately one hundred thousand cubic feet to store compressed air at a maximum pressure of 150 psig. The Shut Off Valve (QSOV)/Butterfly Valve is to isolate the wind tunnel from the air storage system. It is operated easily and quickly because a 90° rotation of the handle moves the disk from a fully closed to fully opened position. The Pressure Regulating Valve (PRV) is to automatically maintain constant pressure in the Settling Chamber(SC) at a preset value during a blowdown. The PRV will perform the quick starting and stopping of the tunnel air flow to minimize the air wasted during transients/interlocks of tunnel control system. To protect the tunnel under emergency conditions, it is having ability to close rapidly in fraction milliseconds. The SC does exactly what its name implies, it helps to settle and straighten the air. The streamlining process starts in the settling chamber, which accepts the air from the wide-angle diffuser, a length for settling to obtain uniform flow and flows into the inlet of the nozzle. The Test section is a compartment where the scaled down models are placed for its testing and analysis of various aerodynamic forces & moments and make visual observations with the help of sensors. The Model Cart(MC) is to support the model, mounted it in either the transonic or supersonic test section and vary the model altitude in pitch and roll during a blowdown based on user requirement. The wind tunnel model is a scaled down model of the actual prototype. This model is mounted in the wind tunnel model cart under airflow condition that replicates the actual flight condition. The Variable Diffuser(VD) is a divergent downstream duct whose role is to slowdown the air velocity from the test section and to increase the pressure just enough to exhaust the air into the atmosphere from the wind tunnel.

### 1.2.1 Flexible Nozzle (FN)

The main function of FN is to create converging-diverging nozzle which helps in accelerating the flow from the settling chamber and deliver a highly uniform flow of air at the desired Mach number in the test section at the downstream end of it. The nozzle is formed by a pair of flexible steel plates (upper plate and lower plate), set to the appropriate contour along the top and bottom of the flow channel. The FN will be controlled and operated by using hydraulic pressure through the hydraulic jack stations. Each flexible plate is held by 17 hydraulic jack stations and also by the upstream and downstream hinge supports. The maximum hydraulic pressure of 2000 psi is used to hold the plates during blowdown and 500-700 psi is used to move plates for contour setting (Mach number setting). Each station indicates positive and negative curvature based on the slope of the plate. These plates needs to be protected from excessive stress due to screw stop setting loose or any other problem such as jamming of the actuating hydraulic cylinders or curvature sensor problems. The over stress is undesirable indication for flexible nozzle health condition and needs to be protect the nozzle against overstressing. The flexible nozzle plates are very thin and long. It is very important to protect them from over stress. The protection is setup by means of seventeen curvature sensing devices (micro Limit switches) mounted on flexible plates along one side for both the plates. Each hydraulic jack station contains 8 limit switches (4 limit switches for upper plate and 4 for lower plate) and each plate contains 68 limit switches (total:136 limit switches). The switches 1&2 (5&6) indicate the Upper plate (Lower plate) positive curvature and form one set. The switches 3&4 (7&8) indicate the Upper plate (Lower plate) negative over-curvature and form one set. This curvature sensing limit switches can be adjusted in such a way that the limits of over-curvature can be readjusted if found necessary. The schematic diagram of curvature sensors placement in FN as shown in figure 2 (CR side : Control room side).


**Fig -2:** Schematic diagram of Curvature senor assembly mounted on nozzle plate

In the existing system, all limit switches outputs of each sting are connected in series and terminated at the FN local control station (LCS). The Local Control Station (LCS) of FN will give the full control and access to operate it. If over stress encounters on flexible nozzle plates, then micro switch will activate automatically. Then Wind tunnel test needs to be terminated immediately and unload the hydraulic pressure. In existing flexible nozzle system, all Limit switches for 17 stations are connected in series from CLS1-1 to CLS1-17 (*CLS- Curvature Limit Switch) and to Relay CR1 for string 1. Same as string 1, 7 more circuits are there for remaining 7 strings. In existing system, the AC power supply 230V, single phase, 50 Hz is connected for all limit switches. The upper plate +Ve curvature sense (String 1) circuit and FN LCS as shown in figure 3.

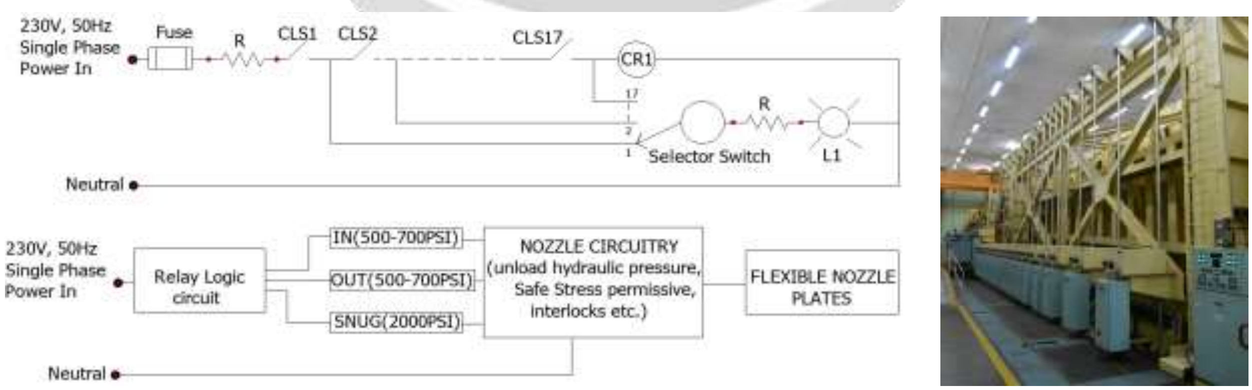
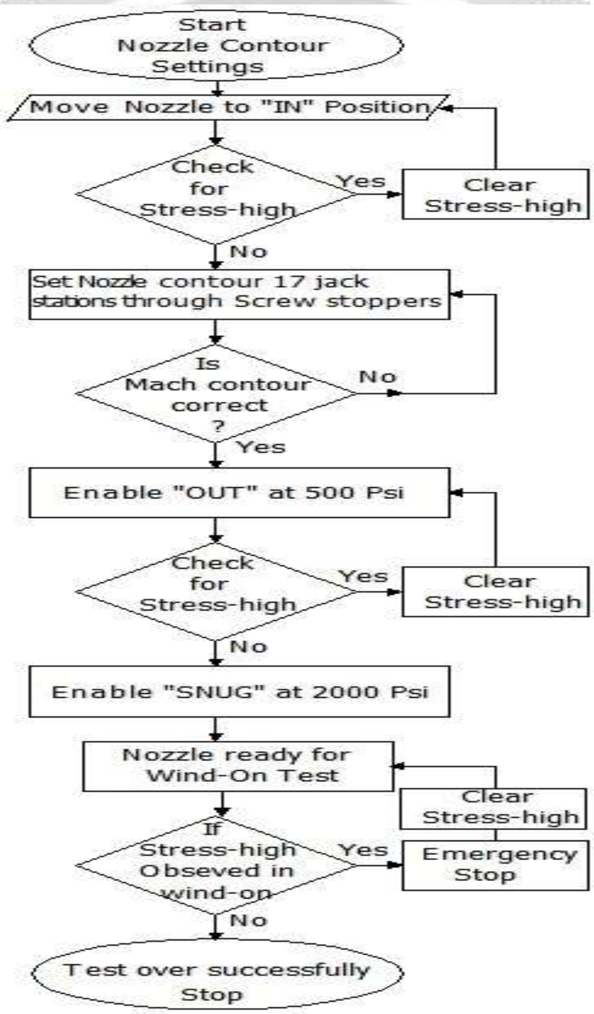



**Fig -3:** Existing system Curvature sense (String 1) circuit and FN

**Flexible Nozzle (FN) Contour Setting:**

The flexible nozzle for Transonic and supersonic wind tunnels are normally made two-dimensional, and this will helps to achieve the control on shapes on two plates, with remaining two plates are being flat. The mach number will be achieved in the wind tunnel test section, where model is mounted and needs uniform flow parallel to wind tunnel axis and constant distribution of mach number in the test section will be additional requirement. The achievement of these conditions in a wind tunnel primarily depends on the nozzle geometry. The flexible nozzle contour settings will be different for each mach number. The FN geometry will be set sequentially in three different type of operations as follows; IN (500-700 psi), OUT (500-700 psi) and SNUG (2000 psi). For Mach contour settings, first activate the hydraulic pressure system to move the flexible plates to innermost contour (IN: 500-700 PSI). Set all the screw stop settings to specified values as indicated the contours. Move the flexible plates against the stops with a hydraulic pressure of 500-700 psi (OUT). Prior to blowdown, a SNUG pressure of 2000 psi generated in the hydraulic system, holds the flexible plates against their stops. Snugging is the automatic operation and it is a part of blowdown sequence. The Mach contour setting procedure and checking for stress on FN as given below flow chart 1.




**Flow chart -1:** FN Mach contour setting and checking for Stress on FN

Every wind tunnel test will conduct after Mach number setting only. The Station selector at LCS is used to detect the station of excessive curvature. The Selector switch will be used for selecting the particular station in between #1 to #17 and L1 shows light indication for the particular station. If L1 not showing the indication, that means Over stress is happening in that particular station and it should be rectify the issue. Due to Wind Tunnel test duration limit (around 30-40 seconds) and series connected sensors, it is highly challenging to identify the stress occurrence at the particular station by scanning through the selector switch. It can detect only one station at a time, where stress encountered initially but after that, it cannot detect the next station until bypass the initial stress station and conduct the tunnel test blowdown again. This process will take more time and requires more tunnel tests for checking the stress status of all stations. The FN stress-high signal is acquiring through the 1.2m Wind Tunnel Data Acquisition system (NI PXI-1010) and it will plot the same. If there is no Stress on nozzle plate, then the FN stress indicator signal will be in mV (milli volts). When the stress happening on FN plates, then the output voltage of FN stress indicator signal is in increasing manner or fluctuations are observed in between 0V to 5V. The various Mach number tests are conducted in the tunnel for identifying the Stress high signal on flexible nozzle plates. In recent Tunnel tests, the stress high observed in the different Mach numbers. The FN stress indicator signal plot without and with stress on FN is as shown in figure 4 below. In the second plot, stress-high is intermittently changing from 0V to 5V continuously observed, then immediately aborted the wind tunnel test. Continuously stress-high observed in the FN stress indicator around 4.2V shown in the plot 3 and then terminated the test. In the plot 4, stress-high abruptly changing in between 1.5V to 5V and this data acquired for longer duration to identify the stress where it is encountering, afterwards terminated the blowdown. By seeing FN stress indicator signal, whether stress is happening or not on the flexible nozzle plates can easily notice but it is impossible to detect where it is encountered. In the plot below, X-axis corresponding to Stress indication amplitude in Volts and Y-axis shows the time in seconds. To overcome this Problem, the real-time health monitoring system implemented and tested for flexible nozzle upper plate +Ve curvature sense in 1.2m Trisonic Wind Tunnel.

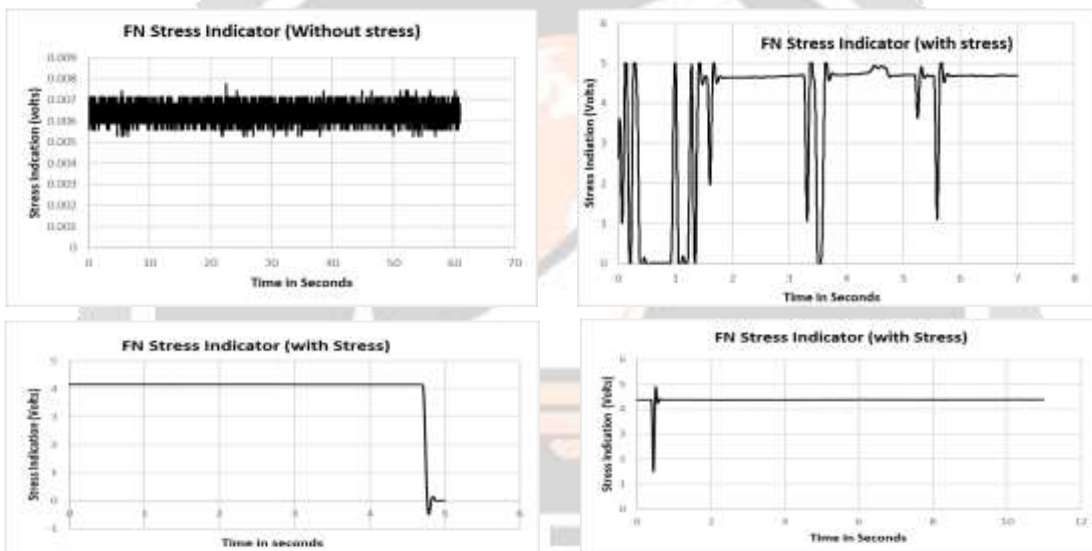



**Fig -4**: FNSTR signal plot without & with stress on nozzle plates

## 2. INSTRUMENTATION AND METHODOLOGY

The real time health monitoring system is developed using NI hardware and LabVIEW software. The real-time health monitoring system for FN is implemented and tested through +5V power supply and NI cDAQ-9136 (Compact Data Acquisition) and NI modules 9403 & NI 9485, as shown in figure 5.

**Fig -5**: NI cDAQ-9136 simulation bench setup for FN

**Table -1:** Configuration of NI 9403 and LS 1-17

| | | |
|---|---|---|
| Pin 1 | DIO 0 | Limit Switch O/P 1 |
| Pin 2 | DIO 1 | Limit Switch O/P 2 |
| Pin 3 | DIO 2 | Limit Switch O/P 3 |
| Pin 4 | DIO 3 | Limit Switch O/P 4 |
| Pin 5 | DIO 4 | Limit Switch O/P 5 |
| Pin 6 | DIO 5 | Limit Switch O/P 6 |
| Pin 7 | DIO 6 | Limit Switch O/P 7 |
| Pin 8 | DIO 7 | Limit Switch O/P 8 |
| Pin 11 | DIO 8 | Limit Switch O/P 9 |
| Pin 12 | DIO 9 | Limit Switch O/P 10 |
| Pin 13 | DIO 10 | Limit Switch O/P 11 |
| Pin 14 | DIO 11 | Limit Switch O/P 12 |
| Pin 15 | DIO 12 | Limit Switch O/P 13 |
| Pin 16 | DIO 13 | Limit Switch O/P 14 |
| Pin 17 | DIO 14 | Limit Switch O/P 15 |
| Pin 18 | DIO 15 | Limit Switch O/P 16 |
| Pin 20 | DIO 16 | Limit Switch O/P 17 |

The CompactDAQ Controller is a reliable, rugged and high-performance embedded controller with industry-standard certifications. The NI cDAQ is a 1.91 GHz Quad-Core Atom, 4-Slot, CompactDAQ Controller and it controls the timing, synchronization, and data transfer between C Series I/O modules and an integrated computer. It has 32 GB non-volatile storage for embedded monitoring and data-logging. It can be operated in any platforms like Windows or NI Linux Real-time. The controller also offers a wide array of standard connectivity and expansion options, such as USB, Ethernet, CAN/LIN, and RS232 serial. The NI cDAQ-9136 chassis is connected with four NI modules (NI 9474, 9403, 9205, 9485). The NI 9403 and NI 9485 modules are configured with NI cDAQ-9136 chassis through NI LabVIEW system. The NI 9403 is a 5V/TTL, 32- bidirectional channels of the digital I/O module for any NI CompactDAQ or CompactRIO chassis. It can be configuring the direction of each digital line on the NI 9403 for input or output. The NI 9485 module is a 8-Channel, Solid State Relay (SSR) and C Series type Relay Digital Output Module. The SSR is a semiconductor equivalents of the electromechanical relay and can be used to control electrical loads without any mechanical moving parts. The NI 9485 module will provide the access a SSR for switching voltages up to 60VDC/30Vrms (current rating up to 750mA/channel or up to 1.2A on 4 channels). The all 8 channels are isolated each other. The configuration of NI 9403 and micro limit switch(LS) output connections are given in table 1. In new system, all micro limit switches of stations #1 to #17 are connected as parallel through +5V power supply and then NI 9403 module of the NI cDAQ-9136 setup. The logic levels will be +5V for Logic HIGH and 0V for Logic LOW. During wind tunnel test, flexible nozzle plates should be hold on that particular screw stop settings with hydraulic pressure. If the plate is bent more than their predefined contour settings, then automatically curvature sensor will get activate and it will shows the RED indication on the real-time display otherwise GREEN indication will display on the real-time health monitoring system. The overall Stress information of the FN is connected to nozzle circuitry for contour settings and control PC through NI 9485 module. The NI 9485 first channel CH0a and CH0b is configured with NI cDAQ-9136 chassis for connecting the +24V Relay. The +24V Relay will gives the two contacts; one for existing nozzle circuitry for contour settings and another one will connect to STRESS Safe Permissive for control PC. The real-time health monitoring system schematic circuit diagram for the string 1 is as shown in figure 6.

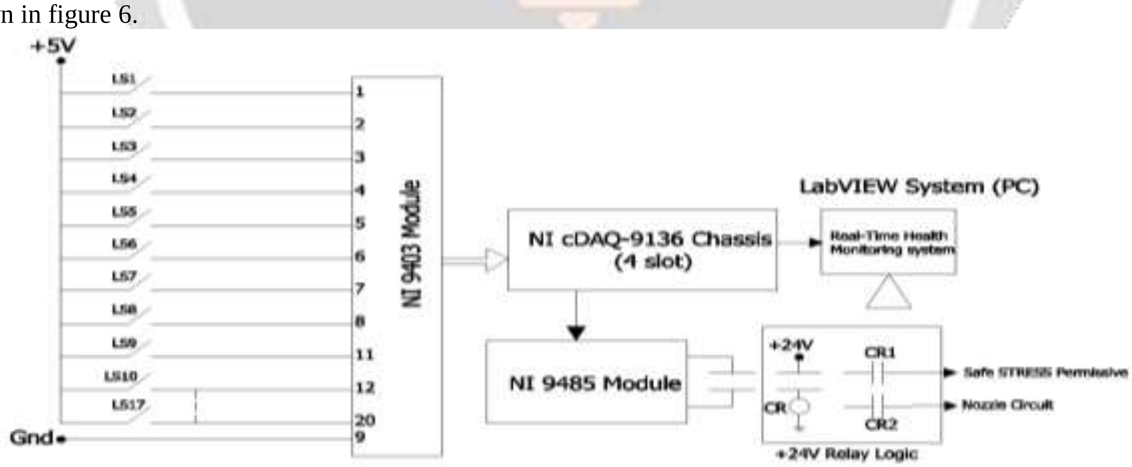



**Fig -6**: The real-time health monitoring system schematic circuit diagram for the string 1

To implement for all stings (136 LS outputs), the real-time health monitoring system requires five more NI 9403 modules and 8-slot chassis (NI cDAQ-9188/89). The five NI 9403 modules are configuring the direction of each digital line for input or output with NI cDAQ-9188/89. The NI 9485 SSR module, all 8 channels CH0 (a&b) to CH7 (a&b) are configured with NI cDAQ-9188/89 for connecting the eight more +24V Relays for eight strings. The real-time health monitoring system schematic circuit diagram for all strings (136 limit switch outputs) is as shown in figure 7.

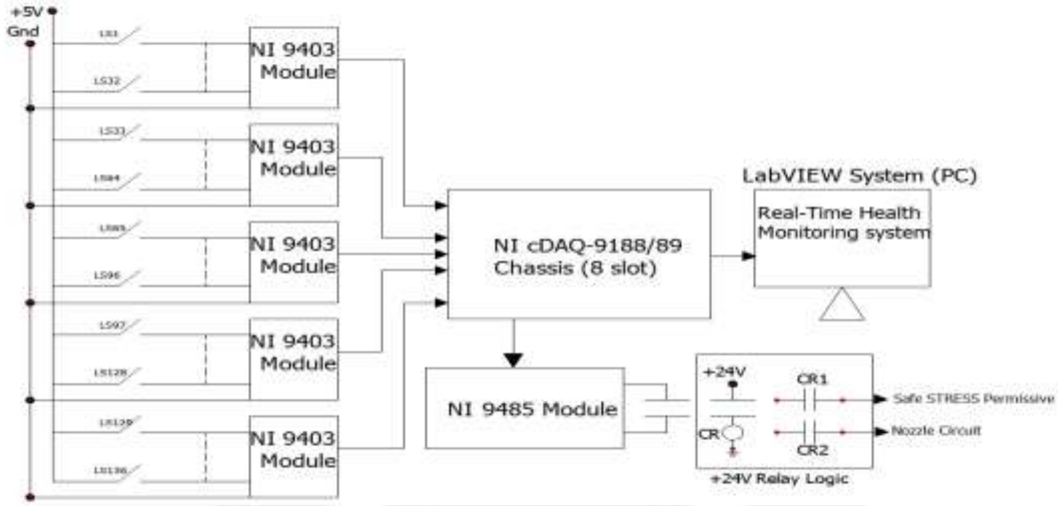



**Fig -7**: The real-time health monitoring system schematic circuit diagram for all strings of FN

## 3. RESULTS AND DISCUSSIONS

The real time health monitoring system is developed in LabVIEW software using state-machine architecture. The system will shows the hydraulic jack station #1 to station #17 on top of the display for both plates and below, it indicates the 136 limit switches status. This system avoids the 230V AC circuitry for limit switches operation and relays. The main advantage of this system is; it operates with +5V DC power supply for limit switches operation and +24V for relays. The FN health monitoring system is an embedded system to monitor the stress on plates and working status of the nozzle plates. With this system, real time information about stress location on the nozzle plates can be identified. For simulation and testing purpose of this system, the Stress signal is generated on hydraulic jack Station #1 and station #4 (Limit Switch-LS1) in the upper plate +Ve curvature sense. The FN health monitoring system shown RED indication for both hydraulic jack station #1 & station #4 (LS 1). The overall FN Stress status also turn into the RED indication. If there is no stress on FN plates, then the system will shows the GREEN Indication for all limit switches and the overall FN stress status also will show GREEN indication. This system has user friendly display interface provides on screen information about stress occurrence. The cDAQ-9136 has 32 GB non volatile memory for data logging, digital stress information on top and bottom plates during wind tunnel tests has been stored. Developed system avoids the multiple wind tunnel tests to detect the stress status for all stations as signals were connected in series and required manually scanning all the stations. The newly implemented system required only one test to detect the stress status of all stations simultaneously and it will saves the lot of time. In this system, solid-state relays are incorporated in the nozzle control circuit to retain the existing functionality of the flexible nozzle control circuitry. The provision has been made to incorporate the tunnel health monitoring signals with the developed real-time system. Figure 8 shows screenshot of developed software in LabVIEW and setup of the real-time hardware.

**Fig -8**: Real-Time health monitoring setup and system display without stress(Green) & With Stress (Red)

## 4. CONCLUSIONS

The flexible nozzle is the important component of wind tunnel. The real-time health monitoring system for 1.2m wind tunnel flexible nozzle provides the efficient control of the nozzle plates along with real-time health monitoring of the system. The newly developed system provides simultaneous locations of over-stress occurrence on the nozzle plates. Developed system can be adopted for any other Trisonic wind tunnel. The real-time system saves the troubleshooting time and improves the wind tunnel productivity. The real-time health monitoring system significantly improved overall speed of operation and efficiency of the 1.2m Trisonic Wind Tunnel.

## 5. ACKNOWLEDGEMENT

I am grateful to the Director, CSIR-NAL and chairman of GVIC, Madanapalle for the kind support and constant encouragement. I would also like to express sincere thanks to Mr. Rajeev G, Chief Scientist, Head and Mr. B. Sampath Rao, Chief Scientist, Joint Head, and Mr. Gopinath P.R., Chief Scientist, Deputy Head, NTAF division, NAL for giving the opportunity to carry out this work. The co-operation and help/support of 1.2m I&C group in carrying out this work is thankfully acknowledged. Also thankful to Dr. D. Sreenivasulu Reddy, Principal, GVIC, Madanapalle, who has encouraged and motivated me to complete the project by providing all necessary facilities to carry out the work in the college.

## 6. REFERENCES

[1]. Ilic, Biljana & Milosavljević, Mirko. (2019). FPGA-based embedded system for wind tunnel variable-geometry nozzle positioning. Scientific Technical Review. 69. 3-9. 10.5937/str1901003I.

[2]. D B Singh., et. al: Design and development of miniature mass flow control unit for Air-intake characterization, Proceeding of SAROD November 2018, Bangalore.

[3]. ILIĆ, B., MILOSAVLJEVIĆ, M., ISAKOVIĆ, J.: (2016, Mar.), Model based stagnation pressure control in a supersonic wind tunnel, FME Transactions. [Online]. 44(1), pp.1-9.

[4]. STEINLE, F., STANEWSKY, E.: Wind tunnel flow quality and data accuracy requirements, NATO AGARD, Paris, France, Adv. Rep. No. 184, Nov. 1982.

[5]. JUHANY, K.A., HUSAINI, H.E.: (2007, Jan.). Investigation of a single jack flexible supersonic nozzle, Presented at 45th AIAA Aerospace Sciences Meeting and Exhibit.

[6]. BALACHANDRAN, P.: Wind Tunnel, in Fundamentals of Compressible Fluid Dynamics, New Delhi: Prentice Hall of India, 2006, pp.346-350.

[7]. ILIĆ, B., MILOSAVLJEVIĆ, M.: A new control system for the flexible nozzle in the T-38 trisonic wind tunnel, in Proc. 6th Int. Sci. Conf. Defensive Technol., 2014, pp.67-72.

[8]. G.K Suryanarayana. et.al., (2018): Mass flow simulation in air-intake models at subsonic Mach numbers using diffuser of wind tunnel as passive ejector, Journal of aerospace sciences & Technologies, Vol.70, No.4, Page No.: 342-357.

[9]. Litwhiler, D. H., “Using Rockets to Unify Topics in an Electro-Mechanical Engineering Technology Instrumentation Course,” Proceedings of the American Society for Engineering Education Annual Conference and Exposition, 2006.

[10]. MEDVED, B., ELFSTROM, G.M.: (1986, Mar.). The Yugoslav 1.5 m trisonic blowdown wind tunnel, Presented at 14th AIAA Aerodynamic Testing Conference.

[11]. Goin, K. L.: "The History, Evolution, and Use of Wind Tunnels," AlAA Student Jour., Feb. 1971.

## BIOGRAPHIES

Devisetty Hari Krishna, born in 1992, passed B. Tech (ECE) at MITS, Madanapalle (JNTUA) in 2014 and Pursuing M. Tech (VLSI&ES) at GVIC, Madanapalle (JNTUA). He joined as Technical Assistant at CSIR-NAL in October 2018. He is currently working at Instrumentation and Controls (I&C) Group, 1.2m*1.2m Trisonic Wind Tunnel, NTAF division, CSIR-NAL, Bangalore. He is involved in Tunnel operations (scaled-down models testing and DAQ), calibration of various pressure sensors and electronic equipment, Wind Tunnel electrical and electronics circuits drawn by using SolidWorks electrical, troubleshooting and maintenance. His areas of interest include Wind Tunnel I&C, Electronics and Instrumentation, Digital Electronics, Microwave RF engineering and RADAR Meteorology.

| | |
|---|---|
|  | Dheerendra B. Singh has an M. Tech in Instrumentation and is currently pursuing his PhD degree in Aerodynamics at IISC Bangalore. He joined the NTAF Division, CSIR-NAL in 2008 and has been working in the Instrumentation and Controls Group. He is currently working as Principal Scientist at NTAF division, CSIR-NAL Bangalore. |
|  | M. P. Chennaiah, born in 1977, Passed B. Tech (ECE) at G. Pulla Reddy Engineering College, Kurnool in 2001, Passed M. Tech (Communications and Signal Processing) at G. Pulla Reddy Engineering College, Kurnool in 2007 and pursuing Ph. D in Digital Image Processing at Jawaharlal Nehru Technological University, Ananthapuramu. He is having 16 years of Teaching Experience in Various Engineering colleges like, SSITS, Rayachoty, GVIC, Madanapalle, MJR Piler. Presently He is working as Professor & HOD in Golden Valley Integrated campus, Madanapalle. He received Best Teacher Award in the year 2016 for getting 100% result in his taught subjects. His areas of interest include Digital Image Processing, Digital Signal Processing, Wireless Communications, Artificial intelligence. |