Pisco Med Publishing

Research progress on health monitoring technology of composite material connection structure

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Abstract: A link structure is a key component of a large composite structure , Plays an important role in ensuring the integrity of composite structures . due to composite material material connection structure Complex nonlinear coupling factor , makes it difficult to analyze the strength and failure modes of the composite connection structure , so , must be Monitoring of the health status of composite joint structures , diagnostics , Evaluation and prediction , gain real-time knowledge of the health of the structure through online monitoring and response to external load , On this basis, the future defects and failures can be predicted , to be able to take action within the appropriate time period , to ensure the safety of composite structure service and achieve maximum economic benefits . with aircraft composite connection structure background , First briefly analyzes the composite material glue connect , damage and failure modes for mechanical and mixed connections ,then focus on wave propagation method , Impedance method , Smart coating supervisor measuring method , Vacuum comparison monitor , Health monitoring of composite material connection structure using optical fiber sensing monitoring and hybrid Integrated Monitoring method (S HM) Technology Research Progress ,Finally, the development trends and challenges of the health monitoring technology for aircraft composite connection structures are discussed . .

Keywords: Composite Connection Structure ; Structural Health monitoring (SHM); nondestructive Testing ; Ultrasonic Guided waves ; Machine Resistance ; Fiber Sensing diagram category number :

advanced composites are used in aircraft structures in a body An important symbol of the advanced and competitive market of the present aircraft _[[], such as composites in Airbus A 380 The amount used in accounts for approximately the structure Total Quality 25%, on Boeing B 787 Is reached in 50%[3], in Airbus Aall XWB up to in52%[4]. due to large composite material Material Structure molding technology limitations and structural design , Process , Check Check , Transport and maintenance requirements , composite structure must be Arrange a number of process detach surfaces , to facilitate the 2 or 2 a The structure is connected as one . connector structure is a large composite knot construction key link , the has for ensuring the integrity of the composite structure important role .

The composite structure has a major connection form of 3 type []. glue consecutive then , Mechanical and mixed connections . the glue connection is connected to a composite structure that is not removable as a whole by means of a binder that need to be connected , is , _ kind of practical and valid , Quick and easy connectiontechnology . Composite material no . The failure mode of glue connection is usually the 4 Form []: ① glue layer destroy ; ② interface invalidation ③ mixed break (and gluelayer clustering destruction with interface destruction ④ is corrupted by Sticky objects . composite material material bonding structure as a multi-layer structure , generally has insufficient strength issues , so the stress and strength analysis method of bonding structure is

Previous research hotspot [i] . mechanical connection with bolted , pin , connection and rivet connections ,

where bolted connections are highly reliable , load -Resilient, Easy to repeat disassembly and maintenance easy to use and so on . Point [8] , is the main mechanism of composite structure in aerospace field Connection mode . The main

failure of the current composite structural bolt connections form with 5 type : ① net section break ; ② cut Destroy ; ③ Split-Pull break ; ④ crush destroy ; ⑤ bolts Loose . _Some scholars about composites Mechanical response of bolt-connected structures and characteristics of failure modes Experimental and theoretical studies , Apply geometric parameter design method to it line optimization design [-11] . mixed connections for composite structures at least for a. with 2 The connection method connects multiple artifacts into one , is usually a a mechanical connection with a thickness and a binding link using the same . The most common use of the in air navigation days is the glue connector - threaded Mixed connections , because they to complement each other , play their respective advantages . current , Some scholars static load test for mixed connections , load distribution and parameterization has done a lot of research. [12-13], But the durability of mixed connections and Fatigue Research to be further strengthened , to ensure glue and machine Armed connections to coordinate work , Create best Connection effect [5,]. hybrid connections can deliver greater load , Delivery path multiple and connector sealed better , is an important trend in composite material connection technology development .

due to the specificity of the composite structure and the composite material even Complex Nonlinear coupling factors that exist in the connectors , make composite material the strength and failure modes of the material connection structure are difficult to analyze []. also subject to process , effects and limitations of hot and humid environments and internal damage , and fiber restrictions on random factors such as laying and fatigue life , to composite connections Structural design and reliability analysis pose great challenges ; another , aircraft composite structures are not only subjected to complex loads (such as fatigue and impact load load), and to withstand harsh environmental factors . (such as lightning and lightning strike) Test Check ,, all of these can cause the performance changes or damage of the composite structure .the connection structure is the most susceptible to damage or failure in a composite structure area , Research has shown that , near 80% The structure of is invalidated by the connection knot construct , Composite structure design is restricted composite material material in aircraft structure _ Step application bottleneck [a].

to guarantee the security of the composite structure and obtain the maximum Economic Benefits , must be healthy for composite connection structure for monitoring ,diagnostics , Evaluation and prediction , through online monitoring get information about the health of the structure and its response to external loads , and on that basis a possible future defect and a To predict , to take action within appropriate time periods . and metal structure relative single _ damage mode for (crack and Corrosion) compared to, Composite structure (In particular connection structure) Defect and damage mode more complex , And not easily observed and detected ; If these injuries are in the The initial generation cannot be discovered in time , can cause bursts of broken bad . recent years domestic and foreign scholars developed a large number of composite connections structure NDT (Non destructive testing ,NDT) technical | the [1617]. $B_{RL}$and[$] the damage type and its corresponding detection method for bolted connection structures are summarized and analyzed. But because of nondestructive testing techniques Limitations , How to structure the aircraft composites (especiallyconnection structure) Damage and its extension for real-time monitoring , and quickly evaluate its impact on aircraft structure security and reliability , is a A challenging topic .

is by using a sensor network that is permanently installed on the fabric Infrastructure Health monitoring (structural Health MONITCR ring , SHM) Technology is a revolutionary innovation for structural integrity Technology , Its application can reduce aircraft structure quality , Improve fly line Security and lower maintenance operation cost [[] . This article takes the aircraft composite Connection structure background , summarizes composite connections SHM Technology Research Progress , discusses aircraft composite materials connect SHM Trends and challenges for technology .

1. aircraft SHM Technology

SHM The technique is to deploy the sensor network on a structure , Get structure State and load change , operations and service environments such as ,, revealing structural damage and structural degradation technology , It sets the smart sensor components , Data acquisition and realtime processing , structure Damage identification ,Hard software systems such as health diagnostics and prediction _ body [1819] . current SHM The application of technology in aerospace is mainly divided into 2 class : _ The class is a usage monitoring ; _ The class is damage monitoring . article main Discussion for damage monitoring SHM technology . if required , source , aircraft SHMtechnology can be divided into active monitoring and passive supervisor test two , According to the principle of monitoring and its sensing technology different , can be further classified as wave propagation method , Impedance method ,, Smart coating supervisor method , Vacuum Comparison monitoring method and strain measurement method , as Table 1 show . Most of these methods are not only suitable for composite structure , same The is also appropriate for metal structures .

with the traditional ND compared to , SHM The pass used by the technology sense components are typically permanently integrated with the monitored structure ,traditional ND up with SHM technical pairs such as tables 2 shows .

In the last more than 10 years , Scholars at home and abroad on SHM Basic theory of and applied technology a lot of research , and step SHM Technology applied to newly developed advanced aircraft , such as Space Shuttle and fighter etc [+] . in the Civil Aviation field , International major aircraft manufacturing public

The Division attaches great importance to SHM Research and application of technology [2224] , Airbus Company etc have completed related to damage monitoring SHMsystem Lab Validation , flying test in progress [a] . with technology increasing maturity, SHM technology will be widely used in all kinds of fly Row . flying vehicle SHMTechnology and the corresponding control concepts real apply , further significantly improve flight based on original structure design Security reliability of structure , based on SHM Technical View Maintenance Decision making and management can significantly reduce maintenance costs for aircraft structures . SHM Benefits of technology like **Figure 1** is shown in .

2. Composite Connection SHM Technology

because of the complexity of the composite connection structure , 1 Section frequently used aircraft SHM Technology not entirely applicable to composite materialsConnection Structure . This section focuses on composite connections between domestic and foreign scholars in the areas of wave propagation and "". SHM vs. discrimination Method Research , and not limited to composite connection structure , Also includes metal and composite connection structure .

2.1 based on the wave propagation method SHM Technology

based on the wave propagation method SHM The mainly includes ultrasonic guided waves (U 1- trasonicguided Waves ,ugw) monitoring , Ultrasonic monitoring(ultrasonic monitoring , UM) Harmony launch (acoustic emission , AE) monitoring etc .

2.1.1 Ultrasonic Guided wave monitoring

Ultrasonic Guided wave monitoring has a far distance to propagate , sensor network Easy Benefits of and structured integration for online real-time monitoring , is currently SHM fields of research hot [[] . based on frequency of incentives , Super

Acoustic Guided waves can be divided into low-frequency ultrasonic guided waves (low-frenquency ultrasonic guided Waves, LGW) and High Frequency Super AE wave (High-frequency ultrasonic guided Waves,

HGW). Current application of ultrasonic guided wave monitoring mainly includes 2 square face : on The one hand, using low-frequency ultrasound guided waves spread far away , coverage product Large features , Monitoring for damage in large-area structures (main If in-plane length is propagated, For example interface debonding damage ,but monitoring precision ; on the other hand, using high frequency ultrasonic guided wave to micro Minor damage

sensitivity , Monitoring structural local damage . High Frequency ultrasound guide

The wave propagates mainly along the thickness of the structure , is more appropriate for a hidden Minor damage in a multi-layer structure that is either attached or bolted the test . so , whether low-frequency or high-frequency ultrasound guided Wave monitor party method , all applicable to composite bonding and mechanical connectionsStatus and damage monitoring .

(1) low-frequency Ultrasound guided wave monitoring

Composite connections based on low-frequency ultrasonic guided waves SHM main The is characterized by the propagation time of the guided waves , Attenuation and reflection properties to characterize Connection structure status (if loose) or damage , applies to geometry structure Relatively simple connection structure (if not explained, Low Frequency Super Sound Guide waves usually referred to as ultrasonic guided waves , It propagates in the board is called Lamb (Lamb) wave) .

Light , and so on [?] (1993 year) research through single One Bolt The Group velocity of the guided wave echoes of the to identify the damage characteristics of the Bolts , but This technology requires hardware system complex , It is difficult to monitor the connection for multiple bolts . &^ wait [[] (year year) on Metal bolt connectionstructure Glue PZT sensor and fire Lamb Wave , According to the guide The statistical analysis of wave propagation time and wavelet coefficients determine bolt loosening . Stanford University Yang and - Chang[+](2006 Year) research attenuation characteristics of ultrasonic guided waves through complex bolted connections , The presents the detection method based on amplitude attenuation for evaluation of bolted connections The integrity of the structure . Shen Fang etc [3132] adopting piezoelectric elastic wave time Invert and focus Method monitoring composite screw connection failure and large Suture of carbon fiber skin in the box section of unmanned aerial drive connection failure , after to develop a voting based , Bayesian beliefs and more Agent Collaboration signal characteristics of the The melting bolt connection structure Status monitoring method [a] .

To summarize , low-frequency Ultrasound guided waves are used primarily to monitor bolt junctions construct is loose , essentially using contact load (preload) ChangeThe effect of the on the ultrasonic guided wave propagation characteristics identifies the connection state . also has the scholar tries to use low-frequency ultrasonic guided wave to monitor multilayer connection structure bolts hole fatigue crack extension [%].

use low-frequency ultrasonic guided wave monitoring glue link structure status or loss hurt 2 [: One is the excitation and receive guided waves are in the bonding area ;The other is to fire the guided waves on the surface of one side connector , guided waves through the sticky The junction is received on the other side of the connector surface . base on ultrasonic guided waves The composite bonding structure monitoring mode as shown in the diagram 2 shows . The main of the are the same. type of monitoring modal transitions [5]. Lowe and 0 & Rating $_7$[+] back to 1994 year to page 1 monitoring mode The type has been studied ,Hay etc [Panax](2003 year) The also explores the use of the The method monitors the aircraft wing-box structure skinning and Sandwich debonding . page 2 species Monitoring mode also successfully applied to aircraft tendons - Skin Adhesive connection and Adhesive patch Damage monitoring , For example, tangent to [pdf] (2006 year) will Piezoelectric smart mezzanine placement on aircraft structural composite patches ,

to monitor the expansion of prefabricated debonding by cyclic loading . These studies the promote the propagation of ultrasound guided waves in bonding structures and not knowledge of modal damage sensitivity .

Monitoring the damage to the connectors of the adhesive connection structure , Wang etc [+] (2 012 year) proposed ultrasonic guided wave to composite material inter-layer break mode I and N hierarchies of and their extensions for monitoring . Liu Country Strong etc [4 °] (A/ year) The presents a method based on the ultrasonic guided wave scattering signal and Time-frequency Analysis Damage Index method , monitoring composite bonding structure interface Damage , and a damage extension test on the tensile tester to verify the validity of the method . Karpenko etc [a]

(2014 year) obtain A using the outgoing ultrasonic guided wave mode . modal Lamb wave to Wardento measure the interlayer fracture mode of a composite adhesive connection structure I and N The is divided into layer and extension , because A0 modal Lamb wave to 2The mode is divided into layer appears very sensitive , can go through A0 modal Lamb wave amplitude value and phase to characterize .

the reinforcement in the wing box of the vehicle is generally mixed by gluing and riveting connect on skin , Its damage monitoring is very difficult . geetha etc [All] (% year) Using a piezoelectric sensor network arranged on the skin. envelope excitation and receive Lamb wave , through small wave points Analysis , to establish an association of damage and signal amplitude ; test Discovery with strong rib damage size increase , received Lamb wave signal amplitude significantly decrease . Janardhanand Krishnan [%] (2014 year) probing Ask for the use of ultrasonic guided wave in situ monitoring composites I Bonding Structure Remove defect of stiffeners , The actuator is arranged in the middle of the stiffeners ., fire out & modal Lamb Wave , is arranged in I Glue structure Mask Skin Sensor reception , using 1 arrives S 0 modal guided wavescharacterize the injury of the stiffeners . with embedded or pasted sensor network envelope technology to motivate and receive ultrasonic guided wave monitoring glue connector status is not The development trend for is .

The problem of weak adhesion monitoring of a adhesive connection currently causes people to shut down Note . The production of weak bonding is caused by construction , Another is service The performance degradation of the glue layer in the process results in . a more feasible approach is to count

value simulations and test methods combine . Matt wait [$] (% $ year) with UAV Composite mask ^ --^ beam adhesive connection structure for research object ,, using semi-finite element method considering viscoelastic damping simulating ultrasonic guided waves propagate , Monitoring adhesive connection through intensity change of transmitted amplitude value 2 type sticky defect (interface off and weak connectors), test and numeric analysis knot fruit indicates that the ultrasonic energy of a bonding connection is highly dependent on the connector Status , If there is a sticky defect the transmission intensity is increased , and There are modal coupling points for high sensitivity to sticky connection states . samaratung etc [4] (2 015 year) The guided Wave is analyzed using the wavelet spectral finite element method propagating properties in composite bonding structures , including adhesive properties Effect of the degradation on the wave speed and time domain attributes .

(2) High-frequency ultrasonic guided wave monitoring

Small loss of medium and long distance inner surface by ultrasonic guided wave of high-frequency thick product hurt with high sensitivity [5], and modal conversions are not obvious [6]. Research has shown that , for sheet structure , frequency thickness lower ultrasound guided waves easily generate multiple modes Lamb Wave , and when the frequency thick product is greater than MHz • mm , the produces a pulse of approximate longitudinal waves [all] . so , compared to low-frequency ultrasound guided waves , High-frequency ultrasound guided waves more appropriate to monitor minor damage inside a multilayer connection structure along a thickness direction to hurt (For example middle hole edge fatigue crack), and the Actuator General Diagonal Probes The, receiver can also use laser detectors .

Dagger (^ compare to etc [+](2007 Year) First High frequency ultrasound application of guided waves in the structure of multi-layer bolted joints of aircraft fuselage , tryCheck is 4 layer Connection structure , but only 1 Layer Structural fatigue stripes , with incentive to 5 MHz for 62° incidence of shear wave sources Ultrasonic Guided waves ,study boundary condition change by simulation and experiment (apply load on each layer by changing the size of the bolt preload) to Effect of high-frequency ultrasound guided waves . 0 ^ calling etc [49] (2015 year) High Frequency guided wave monitoring aircraft multilayer hybrid connection structure in cyclic loading fatigue crack propagation of bolt bore under load , First Use the wedge probe The header motivates a specific model with a frequency greater than the high order modes cutoff frequency State , then using laser interferometer to receive the crack scattering wave , Finally Compare the damage index with the Pulse echo method , Test Results Table The Clear pulse Echo method has high sensitivity to damage .

To summarize , corrode for bolted connections (damage area is greater than Large), Bolt Connection status and

glue connection debonding or layered application Low frequency ultrasound guided wave monitoring , and hidden internal fatigue crack monitoring using high-frequency ultrasound guided waves . for binding structure , glue layer stiffness the and thickness affect the frequency of ultrasonic guided waves of different modes to varying degrees . attributes [+] . Research has shown that , sticky Adhesives help suppress High -priced modal guide waves existing in a multilayer structure of a glue-binding system [$], incidence S. modal transitions for modal guided waves in a glue-link structure , in The produces a coupled, Rayleigh-like guided wave . for bolted connection junctions construct , Ultrasonic guided Wave to frequency , bolt hole distance and size , Bolt hole distribution mode , thickness and rivet tensioning parameters height sensitive sense [+]. for mixed connection structures , because the interface is directly sticky connectors or sealants cause guided waves to decay fast , generally not suitable for high Frequency guided wave detection connection structure status ,Dalton , and so on [Wuyi] (2001 year) for large area monitoring of fuselage double-layer connecting structure , only use less than 1MHz Ultrasonic guided waves to avoid short distance fast attenuation of .

Use guided wave propagation time , features such as attenuation and reflection Monitoring generally applies only to simple geometry (like board , Sticky Junctionconstruct), on complex boundary conditions (such as complex geometry and threaded connections structure) next , guided waves are prone to modal transitions and have wave interference effects , The requires a higher requirement for the signal analysis algorithm . plus , crack etc effect of minor damage on wave propagation is much less than complex geometric profile to wave Propagate impact , also for active monitoring , also needs to be damaged the diagnostic signal before the injury occurs as a reference signal , Environment compensation quite difficult .

2.1.2 Ultrasonic monitoring

Ultrasonic monitoring is commonly used for bolt looseness monitoring , is primarily based on is assumed to be : Ultrasonic transmission and reflection are not only connected with the Screw interface Contact Pressure , and also the physical features of the threaded structure (thermal conductivity) Associated . & 0 ^1« ^1 wait [$] back incentury The use of ultrasonic probes and pulse-echo method to detect bolt Fasteners cracks , The goal is to identify the connection structure before or in the environment before testing for a weak screw state . Krolikowski and szczepek[(1991 year) evaluation of transmission coefficients using longitudinal modal ultrasonic signals contact area and contact stiffness , test to determine effective contact surface product and contact stiffness in relation to contact pressure . Aymerich and Pau [a] (year year) using ultrasonic reflection coefficient evaluation the size and shape of the nominal contact area of the connector for 2, .

Pau and Baldi [+] (2007 year) Research using ultrasonic signals Get the actual graphical pressure distribution of the bolt contact interface , and and Fuji pressure-sensitive films are used to evaluate the quantification of this method Accuracy , test results confirm that ultrasonic technology obtains bolted connections The ability to distribute pressure . jalalpour etc [a](2014 year) for snails The human error that may occur during assembly of the connector structure , proposed _ a technique based on ultrasonic signal and fuzzy pattern recognition to monitor Bolt Connection integrity in Aerospace structures (primarily to consider the snail Bolt Loose), normalized fast Fourier transform by ultrasonic signal transform get signal features , Related to the compression force of the Bolt interface Associate , and in L -type bolt connectors are validated .

with ultrasound guide wave phase greater than , Ultrasonic received a more complex signal Miscellaneous , signal is more difficult to characterize with connection states and related parameters , on

for finer signal analysis processing techniques .

2.1.3 AE monitoring

The application of the AE monitoring in the connection structure is mainly the use of the spiral hole edge crack generation or extension , Bolt Connection interface fretting or gluing When a connection is corrupted quickly releases energy , and transient elastic wave form propagate , received by sensitive sensor , to parse and set bit ae source . Luping etc [+](+ Year) uses the AE technology to characterize the fretting wear of a bolted connection structure , consider preload torque on effect of AE energy . also , Many scholars use AE technology Monitoring composite connection structure failure [+] , such as Xiao and Ishikawa[+](year) take AE Technology monitoring compositefailure damage of

static strength test for screw structures , then monitor for loss The strain status of Bolts [1] , Zhou wait [%] (2015 year) use AE to monitor composite adhesive connectors with adhesive defects cut Damage ,Bak etc [All] (2014 year) Use time-frequency analysis (fast speed Fourier transform) to determine the failure of different connections to produce AE signals frequency , Classification of failure modes for composite connections .

is currently AE monitoring is primarily used for composite material connection Structures extrude and squeeze tests , apply to work in Project AE Ambient sensitivity of the signal , How to establish an actual connection structure status , ae Energy , Amplitude , characterization of cumulative and duration issues such as association .

To summarize , composite connections based on wave propagation SHM The method applies to a wide range of , has the advantage . low-frequency ultrasound guided waves for snails bolt loosening monitoring has advantages , deficiency is less damage detection accuracy ; High-frequency ultrasonic guided wave to the fatigue crack of bolt connection structure Minor damage monitoring has a more obvious advantage , is low on multiple tiers construct decay fast ; Ultrasonic monitoring can better characterize bolt connections Connect status parameters , and AE _ -like damage to the connection structure Test Monitor .

2.2 Impedance-based SHM Technology

The basic principle of the impedance method is that if there are some defects in the structure (such as crack , corrosion etc), Mechanical impedance of the structure will change , pass to determine the degree of variation of impedance measured by a specific dynamic effect and damage degree . Mechanical impedance is generally difficult to measure directly , Multiple is pass over coupling on structural other components (like piezoelectric components , Conductive Components), the uses its electromechanical coupling or resistance characteristics to indirectly characterize . so based on impedance method SHM includes machine resistance (electro - Me chanical Impedance ,EMI)and resistors (Electric Rt sistance,ER).

2.2.1 Machine Resistance

State Monitoring and damage identification method based on machine resistance method main if the mechanical impedance characteristics of the structure change with the paste on the structure piezoelectric tao porcelain The resistance changes of (PZT) have direct coupling off Department [2-63] , compares the impedance spectrum after damage to the structure with its health impedance Spectrum , To determine the extent of structural damage .

from 1995 Year Sun , and so on [+] for the first time, a voltage-resistance based Health Monitoring method since , Many researchers explore the method in mechanicalApplication of bolt connection structure condition monitoring and damage identification [65-67] , focus on Bolt connection features , Characterization of piezoelectric and electromechanical impedance correlation research . ritdumrongkul wait (10) Year) Comprehensive use of piezoelectric The electromechanical impedance characterization of the Tao porcelain components The structural damping caused by the loosening of the screw-- and stiffness changes . Doyle wait [on] (2009 year) use piezoelectric sensorssound - single feature and electromechanical impedance monitoring rapid response satellite Launch Pre-assembly verification test bolts connection structure loose , Theyalso presented the solenoid for the screw connector - on the year The single sex attribute as a hyphen to evaluate index to structural integrity [9]. ' Mr. Wu Wait [+] Year)adopt new piezoelectric Tao porcelain fiber composites (Macro -Fiber composite,MFC) as actuator and sensor , Use its machine the resistance to change characterize bolt loosening conditions . Lim wait [+] Year) proposes a based on Kernel Data Normalization techniques for principal-element analysis to increase the damage monitoring capability of the machine resistance method , and used in composite material [] bolt looseness monitoring for wing and fuselage connectors (machine Resistance methodapplication in aircraft connection structure [/] As shown in 3 ,), but the The method requires a lot of data to be trained . Wandowski etc [a] (2015 year) Set on the skinning and Stiffener connectors on the real airplane wing . 3 type of connection status (main loose nut in different position), Design a 3 Plant Resistance indicator (RMS deviation ,Checkerboard distance and off close by and discusses the sensitivity of the above metrics to temperature , Test The results of show that damage indicators based on associated distances are best monitored .

is currently , How to use machine resistance to monitor the connection of adhesive structure The State has also

aroused widespread concern in the scholars . Na wait [+]((year) Research on the resistance of adhesive connections in corrosive environments anti-law SHM, The purpose is to develop a reusable voltage electric sensor probe . Malinowski etc [] (2014 year) focus on Use the machine resistance method to evaluate the weak bonding status of adhesive connectors , Discussion The adhesive contains foreign bodies (pollution), Moisture pollution and vulcanization is not handled , OK 3 Different damage index changes . Gul$_{lzzl}$ etc [a] (2014 year) the applies numerical simulations and test validation to the application of the machine resistance method in the binding joint status Review price ,2015 years extends the work , The focuses on the feasibility of the electromechanical impedance method and the Repeatable , sensitivity of electromechanical impedance response to adhesive properties is analyzed sensibility [ ].

because the machine resistance method is a local damage monitoring method , in Key considerations in practical applications include : large sensor size small (close to probe area) [all] , The of the excitation signal and its frequency

Select [%] . machine resistance most applied to mechanical connections , heavy point
is bolt loose monitoring , But it's damaged in glue-link structure The application of the
survey is increasingly being watched .

2.2.2 resistor

The resistor is mainly based on the use of conductive components or the structure of their own conductive special characterizes the state or damage of the connection structure . with piezoelectric Tao porcelain [79] or pressure sensitive film [8○] components , latter available structure metal material or carbon fiber [Bayi-]. Peak and WangDejun [+] (2001 year) The change of electric conductivity of piezoelectric plate under high frequency characterization bolts loose . Argatov and Sevostianov[$](+ Year) The presents the bolts based on bolted interface thermal conductivity and resistance variation bolt loosening monitoring , on this basis , They present a formula that reflects the change in the-resistance and bolt tightening torque , through the bolt connection interface placement 2 A method for measuring contact resistance by a conductive sheetintegrity of a bolt connection . jalalpour etc [8 ○] (2013 year) mention out of measurement interface thermal contact resistance to monitor L Bolt Connection Integrity methods , Use pressure sensitive film to establish different screws bolt preload and thermal contact resistance , the Contact pressure of the interface with hot contact resistance .

Shimamura , and so on ™ (+ + year) Use of carbon fiber fracture and layering causes composite material to increase resistance in fiber direction , mentioning Out _ type _ of composite bolt connection structure loss based on resistance change Effect monitoring method , And then from the damage and damage position with the electrode the distance 2 The factor analyzes the accessibility of the method [i] . Kim C H etc [+](2015 year) comment on the method of measuring the resistance of the adhesive connection Price connector defect , through prefabricated defect connection structures and defect-free connections Load test comparison of connection structure resistance , To increase the conductivity of the plus connection structure , Added a 2% to the binder (volume) Fractional) carbon nanotubes .

To summarize , Machine resistance is part of the Local monitoring method , do The tube has been applied to bolted connection looseness monitoring , but requires innovative pressure Design and layout of electrical components for better monitoring ;

and the Resistance method can be used to design a stronger sensing element , in Bolt pine
has advantages in dynamic monitoring , In addition to enhanced composite by specific means
material conductivity , resistance method for qualitative and quantitative diagnosis of structural damage in connection structures
has advantages over , Enables in-place monitoring .

2.3 Other composite materials SHM Technology

from an engineering perspective , Composite Connection SHM more
the needs to focus on minor damage at the junction , especially hole-side cracks and their
Extend . The main overview of this section is the smart coating monitoring method (intellgent

Coating monitoring , ICM), Vacuum Comparison monitoring method (com-
parativevacuum Monitoring, CVM) and fiber optic sensor
Method (fiberoptical Monitoring ,FOM) for
damage Monitoring for composite joints .

2.3.1 Smart Coating monitoring method

Xi ' an Jiaotong University professor Liu Mabao [?] in # Year
The use of nano-technology for aircraft widely used in high-performance anti-corrosion coating
Physical modification of the layer , The is made of a special process with a with damage
attribute for Smart Coating sensor (Smart coating structure schematic and solid
Object Map [?] As shown in figure 4 shows) , developed a coating-sensitive peripheral , Power
resistance to damage monitoring parameters , Polling with a computer Information Intelligence
Coating Monitoring System (intelligentcoating Monitoringsyr
tem , ICMS). Currently the technology has been studied in the AVIC industry
and the Air Force Equipment Research Institute and other units conducted a test and evaluation , knot
Results indicate that ICMS High Reliability , highly practical [a] . is based on a similar think
wants , foreign developed countries also conduct various kinds of intelligent coating research . from
Apply Perspective , Smart coating on surface / Sub-surface damage (crack
Protect Layer Sensor Layer
Intelligent coating
Actuator Layer
(a) illustration (b) Picture
diagram 4 Smart coating structure schematic and physical map [?]
Fig. 4 illustration and picture of intelligent coating structure^)

stripes , corrode) High Sensitivity , and is not restricted by the crack direction , has design , Power low , The therefore has a for monitoring the hole edge of the bolt Significant Advantage ; But additional consideration of bolt connection preload for Smart effects of the coating , Further research is required on whether the binding or internal debonding or the hierarchy is effective .

2.3.2 Vacuum Comparison monitoring method

The Australian Structural Monitoring System Corporation proposed the CVM For direct monitoring of structural cracks . The core of this method is to have a silicone filmVacuum comparison sensor layout in a structural hotspot area (As shown in figure 5 Show, when crack occurs or extends to sensor location , then vacuum degrees changed ,monitored by System [a] . This technology in the euro United states developed country to the forefront , U.S. Civil Aviation Administration , Boeing , Airbus and The U.S.-Australian military and other research teams are working on the 5 many years of durability test and over 2 year after flight test , Airbus will CVM Apply to A380 full-scale fatigue test , Boeing on 2007 The year agreed to CVM included in the pass method of the NDT manual [88 -. but by on The sensor is made of silicone gas suction film ,Environment adaptability and complex clutter signal extraction is still to be enhanced ; Special sensor requires configuration true Air pump and vacuum identification device ,The reliability of the system is also subject to strong ; High sensor cost , restricts its application .

CVM is very effective for monitoring crack propagation in bolt hole edges , only to design the appropriate CVM sensor , can implement a crack extension degree monitor, but CVM Same as Smart coating only applies to surfaces crack monitor , internal delamination and debonding for composite structures the test also has limitations .

2.3.3 Optical Fiber Sensing monitoring method

structural damage or local large deformations can change the structural strain field , Pass monitoring strain field changes , According to the correlation of strain field and damage determine damage to Structures, is based on fiber-sensing structural damage monitor The fundamentals of the measurement [0] . for strain online monitoring ,_ fibre

sensor , such as Bragg fiber grating sensor (Fiber Bragg Grating,FBG), Brillouin or Raman scattering fiber sensing device [[] and all distributed fibre sensor [?].

Murayama , and so on [1] (2003 year) will be based on Brillouin / Raman Scatter optical fiber sensors for hypersonic vehicles hope-x full ruler inch composite structure strain / temperature Monitor , focus on glue The strain distribution of the connector when it is debonding . a serpes etc [3] (2014 year to integrate FBG sensor into composite structure , Monitoring the damage of a composite wall panel with mixed connections , based on number Value optimization design for strain field changes FBG Sensor location , use 3 Test validation of this method . Canal etc [4] (2014 year) Using the embedded composite Connector FBG monitoring The strain distribution in the bonding zone is obtained by the binding and connecting structure gradient , to Evaluate the quality of bonding during service , analysis 3 species FBG monitoring results for embedded locations , FBG in glue connection on configuration [4] as shown 6 is shown in . This is a one a key off method of the note , because the strain gradient can be used to produce a "off " and before extending, evaluate the connector bonding strength .

(2015 year) will FBG embedded in composite connection structure , benefit with FBG wavelength variation characterizing water immersion and applying thermal load should be , to monitor weak adhesion of adhesive structure .

Overall , Fiber-optic sensors can be integrated into composite junction construct internal , Strong design , for monitoring The binding connection has a advantage, but its interface design and layout process needs to focus on .

2.3.4 Mixed Integrated Monitoring method

because different monitoring methods or techniques have their own advantages and disadvantages , the integration of different monitoring technologies is the current research hotspot . Kim J , etc [6] (2006 year) the presents a mechanical vibration analysis and machine

combined Global - A local hybrid monitoring method is used to monitor The loosening of the probe Bolt connection . Doyle etc TM (2009 year) Use pressure Electrical Sensing technology based on wave propagation method and electromechanical impedance method organic Binding , for monitoring bolt loosening . 0 Beers " etc [97] (2015year) A riveting connection structure based on the primary passive SHM technology is proposed "" State Evaluation Method , where the active SHM The technology is based on the piezoelectric sensor Lamb Wave method , Passive is taken based on FBG method , using Fourier analysis and wavelet transform coefficients to get spectral features to characterize the connection state .

Xu Chao [all] (2009 year) A more comprehensive overview of vibration based on the Analysis method (vibration analysis ,VA) Mechanical Bolt connection Structural State monitoring and damage identification . The vibration method mainly utilizes the knot dynamic parameters (such as frequency , modal , modal , Frequency response function, Soft degree and power spectrum, and so on) for status monitoring and damage identification [9]. General Place , due to changes in bolt connection state only local effect on structure Mechanical response , A lower-order vibration that characterizes the overall dynamical characteristics of the structure parameters and Low-frequency pass characteristics are less sensitive to such damage , This vibration analysis method for the aircraft composite connection structure status and micro- Small damage monitoring has greater limitations , So this article does not detail the Research Progress of this method .

2.4 Summary

To summarize , Current aircraft SHM Most technologies apply to status and damage monitoring of composite connection Structures . binding composite failure mode of material connection structure (from damage angle , Bolt Connection the failure mode except bolt loosening can be summed up as Bolt the generation and expansion of micro-damage on the hole side causes), from the monitoring object and its status or damage characteristics , sensor features , system features and anti-environment dryinterference and other factors comparing various technologies , specific table 3 is shown in . need to be noted , The hybrid Integrated Monitoring method is not listed in thetable 3 ,, because its advantages depend on the specific technology or method used . from pass sensor perspective , Piezoelectric

sensors can be used for wave propagation and impedance method , achieving low frequency linear monitoring , Enables High frequency nonlinearity monitoring , easy to paste on structure surface , and easy to embed composite material inside material structure , with clear advantage .

3. Composite Connection SHM Trends in technology and Challenge

3.1 Trends

passes years of development , SHM Technology on an aircraft apply more and more widely . application objects step from simple metal structure show to more complex composite structure , To Monitor physical quantities from change , Temperature extended to multiple injuries , Diagnostic Results are progressively issued from a qualitativeShow to quantitative . so , around composite material connection structure more than sample , feature complexity , damage diversity and concealment , binding compoundmaterial can be designed , from monitoring procedure , sensor innovation design , new supervisor test method or technical discussion composite Connection SHMtechnology is important trends , is an important way to improve their technical maturity .

(1) monitoring process design for composite connection Structures , Manufacturing , service to maintenance full life cycle development , Sensing technology to multiple-field coupling Combination Sensing technology development .

The complexity of the aircraft composite connection structure itself and the service The Harsh nature of the service environment has caused the aircraft composite connection structure the multiplicity of damage and failure mechanisms , Single physical parameter hard to complete Surface represents the service status of composite connections . so , developing multiple fields coupled hybrid sensing networks and combined representations , building composites Multi-mode holographic awareness of the State of the connection structure , Implementing composite material material connection structure from design , Manufacturing , service to maintenance full life cycle Health Monitor , Forming smart composite Connection structure innovative concepts and

Design Method , is future composite connection SHM A For the technology Important development Direction .

in 1^11 , and so on [1○○](2001 year) piezoelectric sensor intelligence proposed mezzanine based on , author [1○1](2011 year) proposed distributed multi-work Energy composite structure State probing technology ,Rakow and Chang , and so on [1○2](% year) developed electromagnetic eddy current thin film sensing technology , toeffectively detects fatigue damage to the perimeter of a multilayer metal connecting structure . diagram 7 for multi-field coupled hybrid sensing Network Diagram , using the electromagnetic Eddy Current film sensors and piezoelectric sensor monitoring composite bolts Damage in the connection structure and its extension , and takeRogowski Coil inductive Lightning current , integrated into multiple field coupling via flexible film sensor network .

(2) sensor to miniaturization , integrated , Intelligent and in- place development , and then seamless integration with composite structures , form with class Sensing and sensing connection status like human neural networks network .

with material science , manufacturing Process , Micro-NA Electronics and Information section Technology and other technologies the rapid development , There are many energy set sensors , driver , Pass Letter and calculation as one multi-function material , for miniaturization of sensors ,, integrated , Intelligent Development provides a technical base [1○3]. development with light Learn fusion of new sensors in technology areas such as biology (Raw Chemical sensor , nano sensor) is an important development direction .

where , using nanotechnology to develop a composite with sensing capabilities material fiber or matrix material , make composite structure itself work Ability _ " body Sensor system , may be the final Solution . For example, to add a carbon sodium duct to the composite structure. In-situ transfer sensor , using resistance changes to monitor structural strain , humidity and temperature degree [1○4]. Current composite connection based on the carbon Sodium metric network SHM technology is a Research hotspot ,This technique can not only monitor loose and local damage to the bolt connection [1○ 5], can also monitor glue connectors

crack initiation of structure , extended and layered damage [1M_M7] .

() monitoring method from linear to nonlinear , from low frequency to high frequency development ; Data processing methods to intelligently development , The diagnostic results are set sex to quantitative development .

The connection structure is a multi-layer knot with high-density geometric features construct , boundary conditions are time-varying and multi-scale nonlinear , Damage is more is small . so , with solid mechanics , Computational Mechanics and non-linear sex theory development , Nonlinear monitoring method (such as nonlinear ultrasoundwave [1o8], Nonlinear guided wave [1o9], Nonlinear solitary wave [all°]) on minute Damage identification and degradation characterization of material micro-properties start displaying Advantage The frequency of the excitation source required by increases accordingly , extends to high frequency area . This is SHM Academic current and future focus .

High-frequency non-linear monitoring methods are characterized by more granular computations , Greater volume of data . from an applied perspective , Academia and industry More emphasis on using artificial intelligence techniques and statistical methods for large numbers of data line handling , for more reliable and accurate quantitative diagnostic results . also , with increasing monitoring parameters , data type also more sample , Large Data Environment SHM Technology increasingly causes academics and industry concerns , want to enter quantitative diagnostic results into the spacecraft life expectancy and visual maintenance decision making process , and feedback to design procedure .

3.2 main challenge

SHM technology belongs to Mechanics , Material , Computer and information , number multiple disciplines cross fields , is integrated integration of multiple technologies , but no to be used extensively on aircraft , still faces many problems , especially is for composite connection SHM, because of its specificity and complexity sex more challenging , the next key to is to address the following challenges .

3.2.1 How to seamlessly integrate a sensor network with a connection structure

connection structure under load complex , High Stress , for Security seek high , especially bolted connections with high-density features , to pass The Sensor network presents a serious challenge to fabric integration , For example how to warranty manufacturing process and interface design compatible with structural design , How to ensure The high reliability and durability of the sensor for the life cycle of the . to for composite bonding structures , You may be able to integrate seamlessly into a composite structure with the same seamless integration of the light/smart interlayer integrated . for composite threaded structures , more practical other One way is based on the bolt connection structure feature , design a similar to diagram 7 show sensor Networks , not embedded inside The structure, but with Bolt , Connection interface organically bound . either way , All require a full engineering trial validation , and being designer and project accepted by the division .

3.2.2 How to eliminate the impact of service environments on monitoring results

SHM An important bottleneck in the application of technology to aircraft is

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