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DURIP PROPOSAL FOR THE AIR FORCE OFFICE OF SCIENTIFIC RESEARCH ON:

STRUCTURAL DAMAGE ASSESSMENT FOR CURRENT AND FUTURE AIR FORCE FLEETS

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ABSTRACT

The proposed work focuses on developing an advanced damage detection scheme for integrated vehicle health management systems. It is based on guided-wave (GW) testing schemes that can interrogate the structure on-demand and evaluate its state. GW generation and sensing using embedded and/or surface mounted piezoelectric transducers, while holding much promise for Structural Health Monitoring (SHM), is not as well understood and have several theoretical and modeling issues that need resolving. Furthermore, still significant theoretical work needs to be done for modeling GW scattering from defects, which will enable their identification and classification. Therefore, experimental characterization of high-frequency waves generated from piezoelectric transducers, their propagation in the structure, and their reflection patterns from different damage types must be perform. This will enable the complete development and validation of the corresponding theoretical formulations for SHM. A high-frequency Scanning Laser Doppler Vibrometer (SLDV) can accurately measure the spatial and temporal variations of the wave field in different aerospace structures. The requested SLDV provides a non-intrusive way of mapping the GW propagation and scattering in structures and will be an indispensable tool in resolving these issues. Once the whole theoretical/experimental/implementation processes are understood, GW schemes using piezoelectric transducers can be designed and implemented for SHM in various aerospace vehicles ranging from aging long-range bombers to next generation spacecraft and reusable launch vehicles.

Introduction and Motivation

Of late, there has been an ever-increasing awareness of the importance of damage prognosis systems in aerospace structures. A damage prognosis system in a structure would be able to examine a structure's health in near-real time, inform the user about any incipient damage and provide an estimate of the remaining useful life of the structure. This increased interest can be attributed to recognition of the enormous potential for life safety and/or economic benefits that this technology can provide. In most present-day aerospace structures, maintenance is performed on a schedule-driven basis using visual and tactile inspection methods, and in some cases, using non-destructive testing (NDT) technology. Maintenance schedules, however, cannot fully take into consideration manufacturing variability and operating conditions, which can result in unexpected failure or functional degradation, which could correspondingly result in lost opportunity costs in terms of revenue or business.

Each structural system has its own usage history and potential for deterioration due to manufacturing variability and/or individual loading and maintenance histories. As seen in Fig. 1, severe usage can lead to a catastrophe due to over-estimation of time for maintenance whereas mild usage represents a lost opportunity cost because of under-prediction of time for maintenance. Under-prediction occurs when high factors of safety are applied to a structure at the time of design, and as a result, structures are rarely pushed beyond the limits of conservative design specifications. These considerations bring to the fore the importance of the use of condition-based maintenance procedures. These would account for operating conditions while not compromising on safety. Operational costs would decrease significantly due to the reduction in downtime of the structural system and lesser labor requirements. Manufacturers could possibly charge in leasing arrangements for system life used during the lease instead of charging simply by its time duration. Moreover, the confidence levels in structure operations would sharply increase due to the new safeguards against unpredictable structural system degradation,
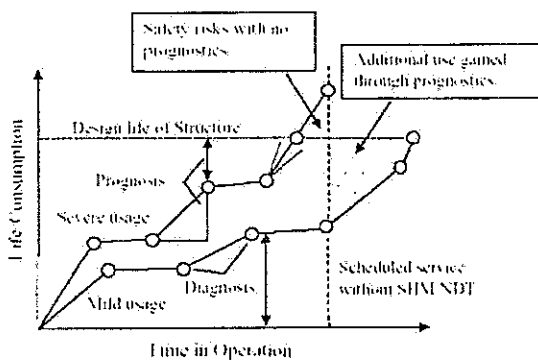

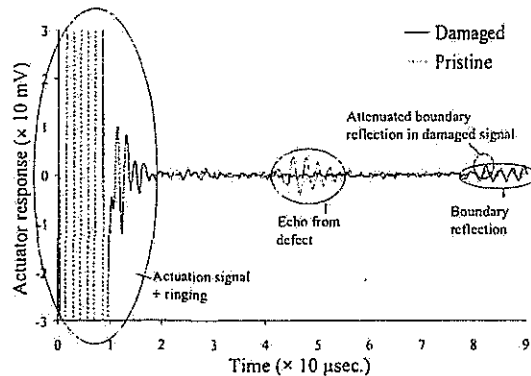Fig. 1: Life cycle maintenance [1]

Fig. 2: Typical experimental results from GW pulse-echo tests for hole detection in aluminum plates

particularly so for ageing structures. Another benefit that would accrue from the implementation of damage prognosis systems is a better understanding of functional degradation by determining how structural systems mature over their lifecycles in the field and use this data to design

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systems that degrade more gracefully. Apart from aerospace structures, a broad spectrum of defense systems can also potentially benefit from the development of such technologies.

Structural Health Monitoring (SHM) is a key component of damage prognosis systems. The SHM component is the part of the prognosis system that examines the current state of the structure for damage and its evolution in time. A SHM system typically consists of an onboard network of sensors for data acquisition and some central processor employing an algorithm to evaluate structural condition. The system utilizes stored knowledge of structural materials, operational parameters, and health criteria.

The importance of damage prognosis and SHM has been recognized and acknowledged by the Air Force Research Laboratory (AFRL) as outlined in a keynote presentation by Derriso et al. [2]. Key SHM focus areas at the AFRL are bonded patch repair SHM, structural "hot spots" SHM and Space Operations Vehicle (SOV) SHM. The former two areas are crucial for reducing the operational burden of the aging aircraft fleet within the Department of Defense. Structural "hotspots" SHM systems will be very useful to have onboard the next generation of manned and unmanned aerial vehicles. This will decrease the time for maintenance, reduce the risk associated with teardown inspection of inaccessible areas, enable using parts for longer by allowing for condition-based maintenance and ensure higher safety levels and better reliability. In addition, these translate into very significant cost and labor savings. In SOVs, also referred to here as Reusable Launch Vehicles (RLVs), the need for SHM systems is even more acute. Very ambitious goals have been laid down for this program, such as aircraft-like operations, 99.98% reliability and turnaround times of the order of hours. SHM would be a key enabler towards achieving these goals. On the present-day civilian Space Shuttle, which is the only existing operational RLV, maintenance is schedule-driven and an expensive, laborious affair. Most of the structural inspection is visual-based and teardown. On an average, it takes 700,000 man-hours, 5 months to complete and constitutes 10% of total operations costs [3]. Yet, despite these intensive processes, as pointed out in [4], during 2001-2002, unexpected system failures occurred late in the launch countdown sequence. Examples of these problems include the ground launch platform hydrogen (H_2) vent-line leak on STS-110 and the orbiter payload bay gaseous oxygen (GO_2) line leak on STS-113. These flaws, resulting from aging or environmental factors, escaped detection by standard preflight tests and were only found late in the launch process. More recently, the Space Shuttle Columbia was tragically lost during re-entry. During its launch, as recorded on video, a piece of foam that came off from the fuel tank hit Columbia's left wing and this is suspected to have damaged the Thermal Protection System (TPS). However, it was impossible to ascertain the condition of the TPS subsequently and this may have proved fatal for Columbia during its re-entry. Such problems will only be magnified in RLVs for military purposes, where the demands and stakes are much higher. An appropriate SHM system can change this labor-intensive, costly and time-consuming inspection practice to an efficient and much less expensive condition-based maintenance.

The schemes available for SHM can be broadly classified as active or passive depending on whether or not they involve the use of actuators. The most significant passive schemes are acoustic emission, strain/loads monitoring and frequency response methods. While the first two schemes have had encouraging results in some demonstrations, high sensor density is a serious drawback for such schemes. They are typically implemented using fiber optic sensors or, for environments that are relatively benign, foil strain gages. Frequency response methods, while being inexpensive to implement, have not met with similar success in SHM due to its limited signal resolution and complex signal processing. Foremost among active schemes are guided-

wave (GW) testing methods. These methods are capable of maintenance checks on demand, unlike the passive schemes. GW methods have great potential, as shown by encouraging results from several initial laboratory demonstrations [6]-[9]

Guided-Wave Testing

Amongst the various schemes being investigated for SHM, GW testing has emerged as a very promising option chiefly because of the ability of GWs to be transmitted over long distances with little attenuation (typically 1-2 m for homogeneous materials and 0.5-1m for composite materials due to their greater GW attenuation), and its active nature that allows "inspection on demand." In addition, GWs produce stresses through the thickness of the structure, enabling defect detection anywhere through the thickness of the structure. Moreover, an SHM system using GW diagnostics would require a significantly lesser density of sensors and actuators compared to other schemes.

GWs can be defined as stress waves forced to follow a path defined by the material boundaries of the structure. For example, when a beam is excited at high frequency, stress waves travel in the beam along its axis away from the excitation source, i.e., the beam "guides" the waves along its axis. They were first theoretically described for a flat plate by Lamb [10]. GW testing can offer an effective method to estimate the location, severity and type of damage. They have been used in the NDT industry for over two decades, where it is a well-established practice. There, GWs are excited and received in a structure using handheld transducers for scheduled maintenance. They have also demonstrated suitability for SHM applications having an onboard, preferably built-in, sensor and actuator network to assess the state of a structure during operation. These transducers are quite different from those used in NDT. The actuator-sensor pair in GW testing should ideally have a large coverage area, resulting in fewer units distributed over the structure. Most commonly, surface-bonded/embedded piezoelectric wafer transducers are used.

The conventional GW diagnostic methods are the pulse-echo (reflection) method and the pitch-catch (transmission) method. In either approach, the actuator generating GWs is excited by a pulse signal (typically a sinusoidal toneburst). In the former, after the actuator excites the structure with a pulse, a collocated sensor "listens" for echoes of the pulse. These are expected from discontinuities such as damage areas and structural boundaries. Since the boundaries are known and the wave speed for a given center actuation frequency of the toneburst is known, the signals from the boundaries can be filtered out, and one is left with signals from the defects, as illustrated in Fig. 2. From these signals, one can deduce the location of the defects, since the wavespeeds are known from the relevant GW theory. In the pitch-catch approach, a pulse signal is sent across the specimen under interrogation and a sensor at the other end of the specimen receives the signal. In either approach, from various characteristics of the received signal, such as time of transit and amplitude of reflections, frequency content, and by using appropriate signal processing techniques, such as chirplet matching pursuits, time-frequency analysis and pattern recognition methods such as neural networks, information about the damage can be obtained. A short primer on elastic waves theory leading up to GW theory in isotropic plates can be found in a book chapter co-authored by the PI [11].

GW testing also presents certain difficulties associated with the dispersive nature of GWs. Fig. 3a shows the dispersion curves for GWs in an Aluminum plate. From these figures, one can see that the wavespeed varies with the product of excitation frequency and thickness of the structure. Furthermore, as can be observed in these figures, at any frequency-thickness product there are at least two modes of propagation. At low frequency-thickness products (up to

approximately 1.6 MHz-mm), only the antisymmetric (A_0) and symmetric (S_0) modes exist. As the frequency-thickness product increases, an increasing number of modes are possible. The dispersion curves for other isotropic plates are of similar shape. For composite plates, these are even more complex, since wavespeeds also depend on the direction of propagation (see Fig. 3b). Hence, the received signals can be very complex. Therefore, to maximize the potential of GW testing, it is crucial to have a fundamental understanding of GW theory. This involves the excitation and sensing mechanisms of GW fields by the transducers, as well as the scattered field due to typical structural defects. Currently, research efforts at the University of Michigan (funded by the DoD) are directed towards resolving issues in these areas, as explained in the next section.

Current DoD-funded Guided-Wave Structural Health Monitoring Research at the University of Michigan

At present, there are two GW SHM projects in progress in the Active Aeroelasticity and Structures Research Laboratory (A^2SRL) that will be directly affected by the proposed study. One is related to development of novel transducers for large area SHM, and is funded by the AFOSR (Grant # FA9550-06-1-0071). The other is focused on diagnosis and prognosis of space structures for Integrated Systems Health Management (ISHM), and is jointly funded by NASA and the DoD under the Space Vehicle Technology Institute (Grant # NCC 3-989), within the Constellation University Institutes Project.

For the latter, 3-D elasticity based models have been developed for describing the excitation and sensing of GW fields in isotropic plates due to finite dimensional circular and rectangular monolithic piezoelectric wafer transducers [12], as well as rectangular macro fiber composite transducers [13], these been originally developed at NASA Langley [14]. MFCs
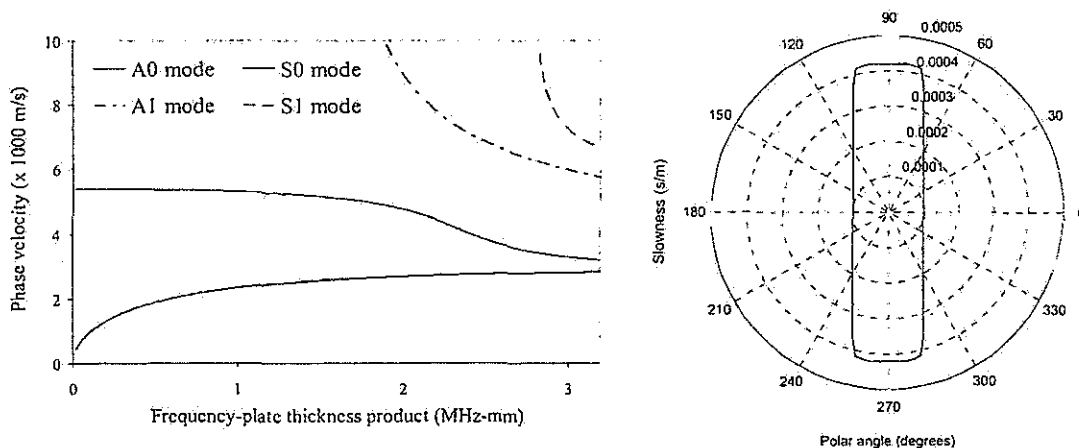

Fig. 3: a) Phase velocity dispersion curves for the first four Lamb modes in Aluminum alloy (left) and b) Slowness curve (inverse of phase velocity versus wave propagation angle) for 0.5-mm thick unidirectional graphite-epoxy plate at 100 kHz, S_0 mode

utilize interdigitated electrode poling and piezoelectric fibers embedded in an epoxy matrix (Fig. 4), which results in a high-performance piezoelectric transducer with strength and conformability

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characteristics much greater than that of a conventional monolithic piezoceramic. Some sample plots of the GW field are shown in Fig. 5.
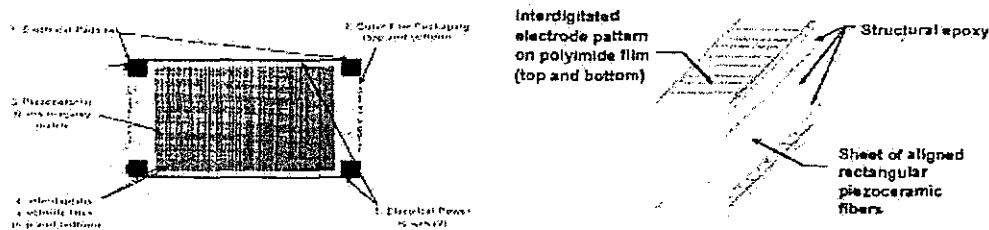

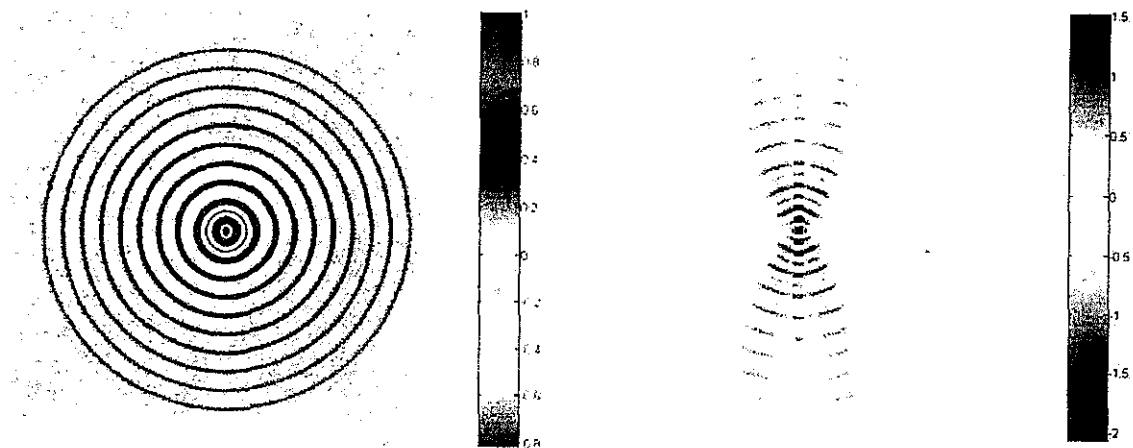Fig. 4 a) (left) The packaged MFC and b) (right) The components of a MFC actuator [14]

Fig. 5 Harmonic GW field in terms of surface out-of-plane displacement at 100 kHz, A_0 mode in a 1-mm thick Aluminum plate due to a) (left) circular actuator of diameter 0.5 cm and b) (right) a 0.5 cm × 0.5 cm square MFC actuator. The scales are arbitrary and for clarity only 20 cm × 20 cm of the plate is shown, with the displacements being set to zero for $r > 9$ cm.

This work fills in a crucial gap in the related literature for GW modeling in plates. Earlier efforts elsewhere developed either elasticity-based models for 2-D GW propagation (ignoring variations along one direction in the plane of the plate) or reduced order models (such as Mindlin plate theory) for finite dimensional transducers. The problem with the former is that one never gets a true visualization of the 3-D field, and with the latter, they only work at low frequencies and can model only one of the several possible modes. The models developed at A^2SRL have shown encouraging results in initial experiments using piezoceramic wafer actuators and sensors (see Fig. 6). However, there are two limitations of using piezoelectric wafer sensors – one is that they always add some local mass and stiffness at the point of measurement. Due to this, there is some scattering of the GW field, and this affects the measurement of the GW field. This might partially explain why the results in Fig. 6 show better agreement with the theoretical curves generated for transducer dimensions smaller than the nominal values. Two, one never gets a complete experimental picture of the spatial variation of the GW field over the plate surface (for example, the experimental
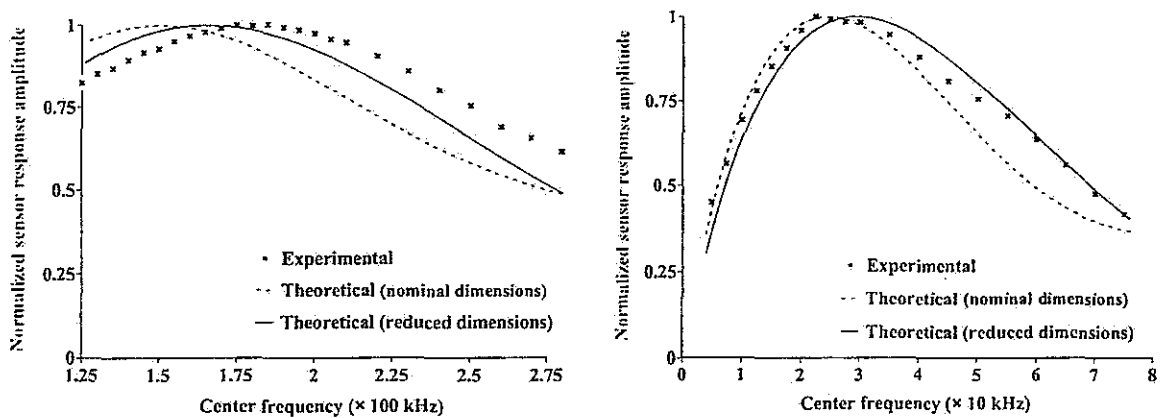
Fig. 6 Comparison between experimental and theoretical sensor response amplitudes in the rectangular actuator experiment for a) S_0 mode (left) and b) A_0 mode (right)

version of the surface plots in Fig. 5). Adding more sensors might help this cause, but it further worsens the problem of added mass and stiffness, and the measured GW field would then suffer even more due to the multiple scattering sites at the sensors. An extension of these theoretical models for composite plate structures is presently under development, and will also need to be experimentally validated.

Most GW SHM efforts (including the above project) to date have used monolithic piezoceramic transducers. These might be unsuitable for permanently mounting on structures due to their brittle nature. In the other project under investigation at the A^2SRL, this issue is being addressed by developing mechanically flexible, power-efficient and long-range transducers. These are based on MFC transducer technology, described earlier. In this project, special MFC elements will be designed for GW SHM to satisfy the unique demands for effective implementation of this technology. The interdigitated electrode pattern will be designed such that each electrode finger has (or small groups of them have) independent actuation controlled by an electronic switch as illustrated in Fig. 7. By selectively exciting certain fingers, a length very close to the desired length of the actuator can be excited, generating a chosen GW mode at a desired wavelength. Thus, certain fingers of the electrode pattern may be inactive, while others are excited. In this case, a certain set of desired wavelengths can be excited by particular combinations of electrodes. Similarly, when they are used as sensors, the voltage output over a length close to the desired length can be recorded by monitoring the voltage between appropriately chosen fingers, so that the sensor size can be made as small as desired, thereby maximizing the sensor response. The pattern will be designed such that the wavelengths expected to be used for the particular application can be optimally excited, which depends on the structure's unique properties, service conditions and susceptibility to specific defect types. Another proposition that will explored is the design of electrode patterns for comb transducer-like actuation, by designing finger clusters at half-wavelength periodic intervals for wavelengths expected to be used. This will achieve very high modal selectivity, and significantly improve the defect resolution and characterization, as discussed above. Since temperature variations will change the baseline characteristics of the wave propagation, it may be actively adjusted with proper electrode spacing to ensure operation at an optimal point continuously. This will also be investigated in the transducer design. The fabrication of the proposed actuator/sensor element will be done in close collaboration with NASA Langley, the pioneer of MFC development.

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After developing a combined actuator/sensor MFC element that is specially adapted for SHM as described above, it will be integrated in a quasi-circular pattern as indicated in Fig. 8. The quasi-circular pattern will use several radial or rectangular transducers laid along the radii of the circular array at different angular locations, and operated in pulse-echo mode. The exact number of elements that will ultimately be used will depend on the application in question and directionality properties of the individual transducers, which will be carefully studied for this design. Each transducer will excite GWs in the radial direction. The effectiveness of curved finger electrode patterns in generating divergent beams for scanning one sector at a time on the structure will be quantified. With such a circular array, it would be possible to perform a large area inspection of the specimen without compromising on the range of inspection. In addition, such a configuration allows for specially designing each transducer to match the dominant wave propagation characteristics of the sector under interrogation, which would make this a very effective method to handle SHM in composites. Each transducer is excited in their turn, one at a time, with a sinusoidal toneburst and after the period of excitation, it listens to the echoes received from discontinuities along with the other transducers, which are also "listening." After all echoes are obtained, using a digitally controlled central switch, the excitation signal is used to actuate the next transducer and the same process is repeated in a radar-scanning fashion for each transducer. Owing to the fact that only one transducer is excited at a time to focus on one sector, the power requirement for such an array is drastically lesser than that for a comparable linear array where all actuators are simultaneously actuated for scanning any given part of the structure. This raises the prospect of it being a better candidate for integration with an onboard power system and wireless communication device to realize a truly independent and compact onboard SHM device. In addition, due to the directional focusing capability of the individual elements, the array will have a much longer inspection range when compared to omni-directional arrays, thus allowing for a lesser density of transducers on the structure.
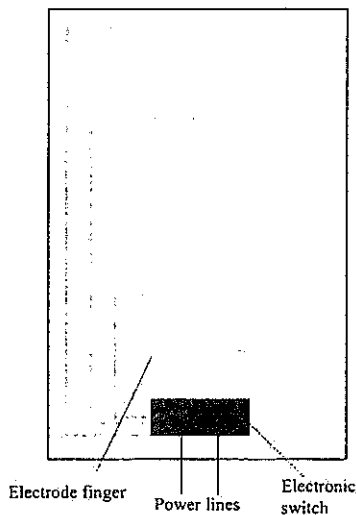

Fig. 7: Schematic of electrode pattern on proposed VLIDT

Electrode finger   Power lines   Electronic switch

Plate specimen under inspection

Direction of scan

Active MFC

Defect

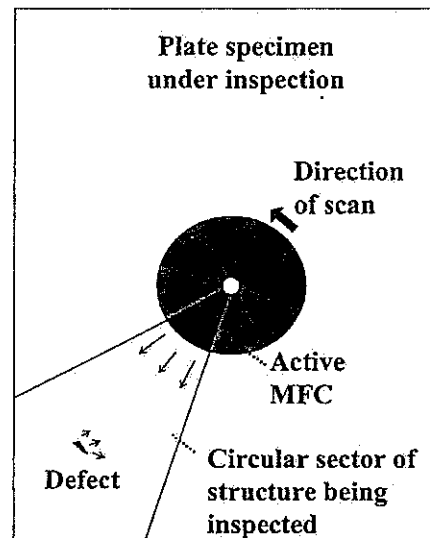Circular sector of structure being inspected

Fig. 8: Schematic of proposed CARS

One crucial aspect to the development of the above array configuration is a clear understanding of the GW mechanics of each individual transducer. To model that, an extension of the approach used in the SVTI project described first is being worked on presently. Once that is completed, it will need to be validated experimentally. In this case, the need for a non-invasive sensor capable of covering a wide extent of the structure is even more acute – the ability to test and calibrate the extent of the focused GW field actuation and sensing capabilities of each individual transducer is crucial to the success of the planned transducer system. Without experimental confirmation, any claims about underlying mechanics would be baseless.

Another key piece of the puzzle for both these projects is the signal processing scheme used for diagnosis. Ideally, the output of this step is the decision whether damage is present, and if so, information about its location, type and severity. The more detailed the information available, the better the prognosis in terms of remaining service life of the structure. For GW pulse-echo based testing, the algorithm must be capable of isolating individual reflections from defects in the structure, if any, which could be overlapping and multimodal. In addition, they should be able to estimate the time-frequency centers, the modes and individual energies of the reflections, which would be used to locate and characterize defects. Finally, they should be computationally efficient and amenable to automated processing. Efforts in this direction have also been initiated at the University of Michigan [5]. A new algorithm employing chirplet matching pursuits [15] followed by a mode correlation check has been developed for single point GW sensors. It has several advantages over conventional time-frequency representations in all aspects and these have been demonstrated using numerical simulations and experiments in isotropic plate structures. For example, experiments were conducted with a 1-mm thick Aluminum plate structure, the schematic of which is shown in Fig. 9a. The 1-mm thick aircraft-grade Aluminum alloy plate was supported on two support struts on two edges and the other two edges were free. Surface-bonded PZT-5A piezoceramic transducers were used. The actuators were excited symmetrically with a 2.5-cycle Hann-windowed sinusoidal toneburst of center frequency 175 kHz, thereby predominantly exciting the S_0 mode. After baseline signals were recorded for the pristine condition, artificial "damage" sites in the form of C-clamps were introduced. The C-clamps cause local stiffening and addition of mass in the structure over their contact area, causing incident GWs to be scattered from them. The difference signal between the pristine and "damaged" cases is shown in Fig. 9b. In this case, the spectrogram is incapable of resolving the overlapping S_0 mode reflections from the two clamps (Fig. 9c). On the other hand, the proposed algorithm proved its prowess in this case too. The chirplet matching pursuit step was able to resolve the overlapping S_0 mode reflections as well as the S_0 and A_0 mode reflections from the boundary (Fig. 9d). The mode correlation step correctly identified the modes, thereby allowing accurate radial location estimates of the clamps (Errors in location: C1 – 3.6%; C2 – 8.8%).

However, one limitation of this algorithm is the assumption that defects behave as point-scatterers. Thus, it cannot by itself distinguish between different defect types. Also, only a crude estimate regarding defect size can be made using the error in location using different transducers. To get a better estimate about size and to reliably infer the defect type, it is crucial to use damage models in conjunction with some pattern recognition algorithm. Therefore, theoretical models will be developed for GW scattering from different damage types. Damage types considered will be cracks, impact damage in the form of dents/holes and delaminations and debonds (for composite structures). Again, once these models are developed, experimental validation will be necessary.

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It is, therefore, imperative to have a non-intrusive high frequency guided wave sensing system to support the different SHM studies being conducted under Air Force sponsorship at the University of Michigan's A²SRL. The system must be capable of easily sweeping and taking high-frequency measurements across large structural areas.
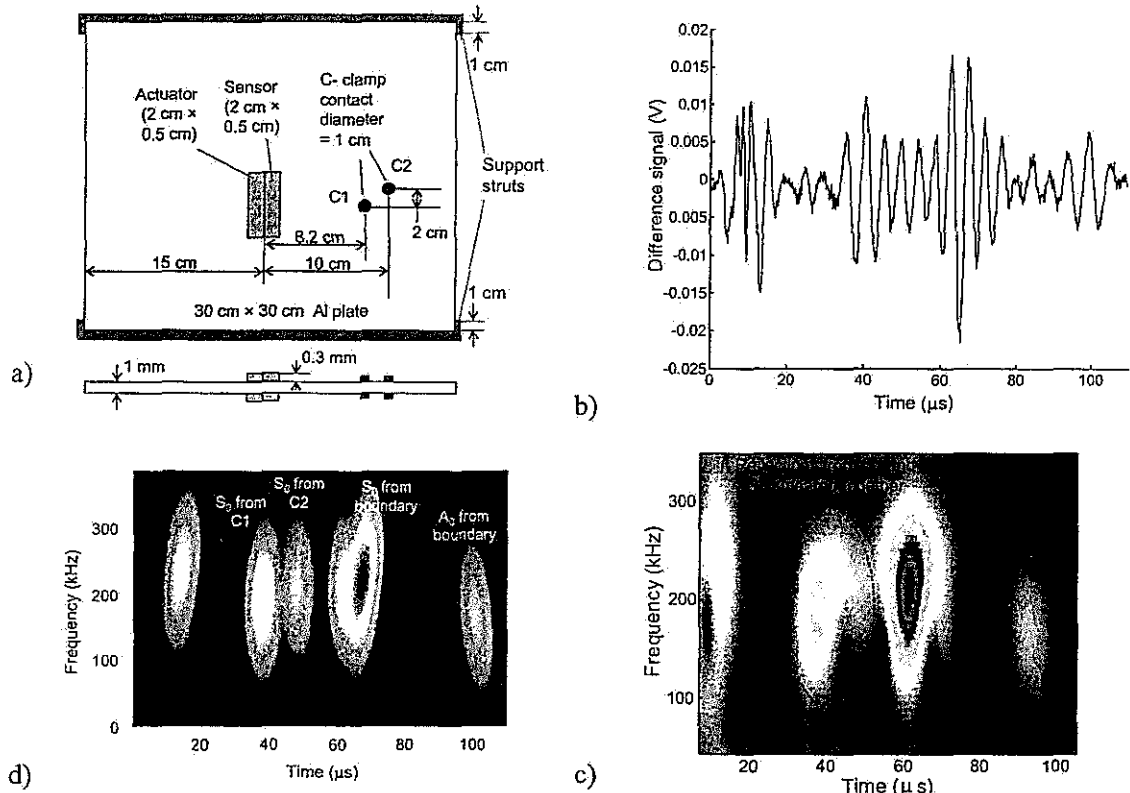

Fig. 9: Illustration of the capabilities of the developed chirplet matching pursuit algorithm. From top-left, clockwise: a) Schematic of experimental setup with two closely spaced artificial damage sites in the form of C-clamps; b) Difference signal between pristine and "damaged" states; c) Spectrogram for the same signal, which cannot resolve overlapped reflections; d) Interference free TFR generated from chirplet matching pursuit algorithm (implemented using *LastWave* [16], which is freeware) which was successfully used to isolate overlapping reflections, identify the GW modes and estimate the radial locations of the clamps

Required Instrumentation – Scanning Laser Doppler Vibrometer

A Scanning Laser Doppler Vibrometer (SLDV) proves to be the ideal instrument for fulfilling the above need. This computer-controlled laser scanning device processes the information to extract motion, mode shapes, FFT, and other digital signal processing functions of the dynamics of the structure. It operates on the Doppler principle, measuring the frequency shift of back-scattered laser light from a vibrating structure to determine its instantaneous velocity and displacement at that point. Therefore, it can precisely and quickly measure wave amplitudes, and because it uses a laser, it is a non-contact measurement device. This eliminates problems associated with contact sensors, i.e., mass loading and local stiffening. The PI has identified

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Polytec PI Inc., Auburn, MA as a supplier of such equipment. Polytec PI, Inc. supplies SLDVs manufactured by the German company Polytec, which is one of the industry leaders in laser-aided measurement technology. The Polytec PSV-400-M2 series SLDV with a 2-channel, 1 MHz Data Acquisition System, shown in Fig. 10, will be ideal for our research needs. The bandwidth will be perfect for GW SHM, where frequencies of the order of a few 100 kHz are typically used. The PSV-400 series SLDV consist of a scan head, a controller unit, a PC-based processing/data management system and a junction box connecting the various units. The scan head consists of XY deflection mirrors, a live color video camera and an LDV sensor. The computer-controlled deflection mirrors automatically and rapidly steer the laser beam to the desired position on the target structure. The live video camera displays the laser beam on the target and allows the user to draw a grid of desired measurement points right over a video image. The LDV sensor comes already mounted into the scan unit and can be used stand-alone when scanning is not needed. The data management system comes equipped with software allowing easy visualization of the collected data. It allows for spectral presentation and 3-D visualization of the vibration data overlaid with the video image of the structure. Detailed specifications of this instrument are provided in the Appendix.
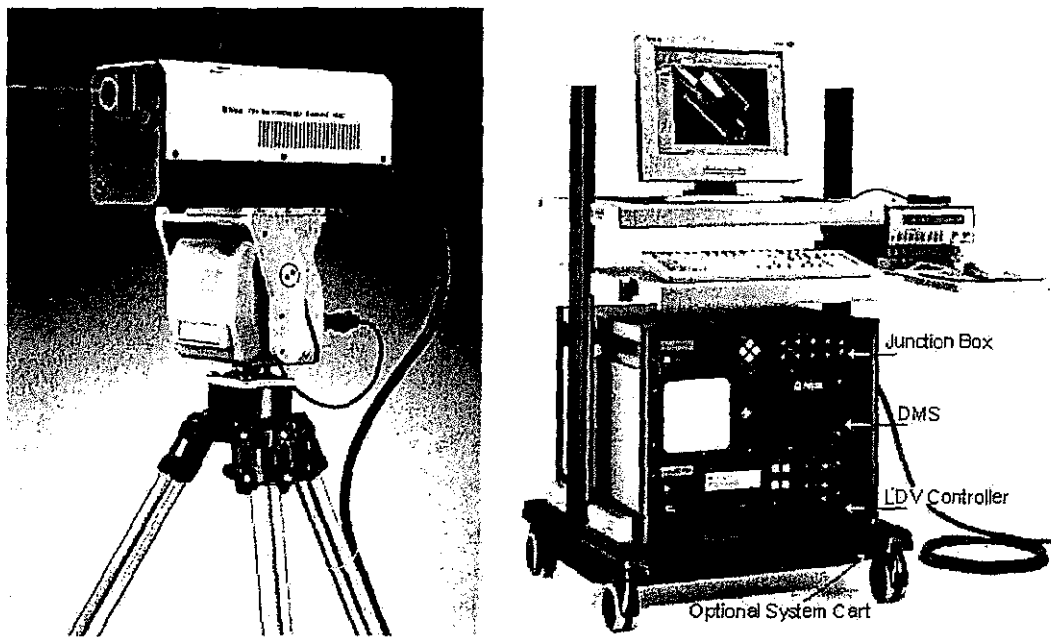

Fig. 10: The Polytec PSV-400 Scanning Laser Doppler Vibrometer and the associated processing electronics

A summary of the key features of this instrument is as follows:
- Displacement resolution of the order of 1 nm, stand-off distances from 0.4m to several hundred meters and from a wide range of surface finishes.
- Velocity range from 0.3 μm/s to 20 m/s.
- The scan head displacement mirrors have a $40° \times 40°$ field of view with a typical settling time of < 10 ms, and a position resolution of $0.002°$.

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- 72x zoom capable live video camera with auto focus.
- A computer workstation with a 2-channel 1 MHz data acquisition board.
- Time domain data acquisition optional feature to capture elastic wave propagation across a surface.
- Superior noise performance.

The Proposed Equipment and Its Relation to Other DoD Objectives

As discussed, once the requested SLDV is in place, it would be an indispensable aid in the extensive GW theoretical modeling, the planned design and development of anisotropic piezocomposite actuators for GW SHM and in our efforts to accomplish the radar-scanning scheme for large-area coverage of aerospace structures. Moreover, while the ongoing SHM projects focus on SHM for next-generation spacecraft and new/aging aircraft, the developed schemes can also be applied to rotorcraft and other civil/mechanical structures. Thus, the technologies under development in this project have the potential to enable SHM and condition-based monitoring in a wide gamut of applications.

Apart from the SHM projects, another Air Force sponsored program that will directly benefit from such equipment relates to the Michigan/AFRL Collaborative Center in Aeronautical Sciences (MACCAS). This is an ongoing partnership with the Computational Sciences Center of AFRL/VA. MACCAS consists of a number of highly accomplished faculty members along with research staff and graduate students from the University of Michigan and the Michigan State University. While the initial focus for the MACCAS is on developing and integrating all of the computational tools required to perform reliable, high-fidelity, multi-disciplinary analysis of airbreathing, hypersonic vehicle concepts, it also addresses low-Reynolds number flight conditions. This includes both high-altitude long-endurance aircraft as well as micro aerial vehicles. The PI is directly involved in this second aspect of the Center, where fluid-structure interaction issues will be addressed at low Re numbers. In support to that, experimental work is expected to be conducted at the University of Michigan in highly-flexible flapping wings. A SLDV like the one being requested under this DURIP proposal will have a fundamental role in supporting the studies. Experimental characterization of this new class of wings will provide transient data that directly impact the validation of the high-fidelity computational codes being developed at AFRL.

Apart from supporting graduate-level research, our ongoing projects also benefit from the active involvement of undergraduate research assistants, some of whom are selected through the University of Michigan's University Research Opportunities Program (UROP). UROP was created to improve the retention and academic achievement of under-represented students on the University of Michigan campus. Today, the program includes both minority and majority students but maintains its original emphasis on underrepresented minority students and an emerging focus on women in science students. Working on these projects presents a very valuable learning opportunity for the involved undergraduate students. It gives them valuable insights into and excites them about the research process, and concurrently proves beneficial for the attainment of the project's research goals. With the SLDV in place, there is even more scope for education and involvement of undergraduate students, and enhance their understanding of GW propagation. This is also in tune with the DoD's mission to enhance the institution's ability to educate future scientists in SHM, a research area whose importance is duly recognized by the AFOSR.

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In summary, the capability that will be created with the requested SLDV will contribute towards creating a state-of-the-art facility for critical DoD research and education to be performed by world-class students and faculty at the University of Michigan.

Facilities

The main facility at University of Michigan to develop this study is the *Active Aeroelasticity and Structures Research Laboratory* (A^{2}SRL), supported by the *Adaptive Materials and Structures Laboratory* and the *Composite Structures Laboratory*. These three laboratories have developed extensive manufacturing and testing capabilities at the active materials, device, and structural levels. Their capabilities can be loosely grouped as 1) active materials and structures manufacturing, 2) active material systems and device level testing, and 3) controlled structures and applications level testing. Special facilities and equipment available in these laboratories that will be pertinent for this work are:

- 3'x 6' autoclave that provides computer-controlled temperature and pressurized environment test conditions (up to 800 ^{0}F) and advanced composites fabrication capability for integrated sensor/actuator into the structure.
- Industrial oven (1000 ^{0}F) for basic temperature tests.
- MTS testing machines capable of simultaneous mechanical and thermal loading.
- Computer-controlled oscilloscope for high frequency guided wave monitoring and signal processing.
- Piezo power amplifiers and high frequency signal generators

In addition to these hardware related capabilities, extensive modeling and design software have been developed for active materials and structures, including GW propagation and damage diagnostics. *DISPERSE*, which is well-tested and validated software for GW dispersion and slowness curves in several complex structural configurations (including damping models) is available. Several computational facilities and FEM solvers are also on hand for this project.

Costs

The total cost for the high-frequency Scanning Laser Doppler Vibrometer and its components described in this proposal is $258,720.00. A detailed quote is attached in the Appendix.