Principles of Using Integrating GPS and Triaxial Accelerometers in Surveying Displacement of Large Span Bridges

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Key words: Health monitoring,GPS, Triaxial Accelerometers

SUMMARY

Detailed information about the characteristic deflections of large structures such as bridges and tall buildings can help to determine the "health" of such a structure as well as to evaluate whether such deflections are the same as those that the structure was designed to tolerate. Due to the ever increasing size of some of these structures, a reliable and accurate health monitoring system could detect uncharacteristic vibrations and deflections, and help prevent disastrous consequences. The use of kinematic GPS has been shown on many occasions to be a viable tool for monitoring the deflections of large structures through its ability to provide cm level precision, at a rate of up to 10 Hz with real time capabilities and with the rover receiver being able to be positioned at a distance of up to ~20 km away from the reference (ideal for long bridges). In addition, accelerometers have been proven useful for such monitoring, allowing precise readings at rates of up to 1,000 Hz. However, both systems have their limitations. GPS is limited partly by multipath and cycle slips as well as the need to have good satellite coverage, whilst accelerometers are limited due to the fact that their readings will drift with time. The integration of the two systems ,however, results in a hybrid arrangement that eliminates the disadvantages of the two separate units. his paper presents an integrated monitoring system, consisting of Leica CRS 1000 series an SR530 dual frequency code/carrier GPS receivers and a Kistler triaxial accelerometer. Two units are physically integrated and their data synchronised. Using spectrum analysis, main natural frequencies are established from the hybrid system. A simple data processing algorithm is presented, as well as the results from field trials to show the potential of such a system .this paper presents the principle of GPS and triaxial accelerometers in large span bridge surveying, advances in real-time GPS deformation monitoring for bridge,GPS satellite geometry and its impacts on bridge deflection monitoring,the principle of deck (of bridge)gemetry adjustment and 3. Coordinate Transformation and Attitude Determination for the Bridge Deck.

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1. INTRODUCTION

Bridges and other flexible structures are designed to withstand calculated and predicted forces,such as wind,traffic, tidal loading, and other extreme loading such as earthquakes, floods and typhoons. These variables are the main consideration factors in bridge design and govern,in part,the structure's characteristics and life expectancy. In recent years a large number of bridges have been found to incur damage that is attributed to im pact and fatigue. Obviously, the increase of vehicular weight and traffic volumes in the last 2 to 3 decades has also contributed to the potential for damage. For instance,about one-half of the approximately 600,000highway bridges in the United States were built before1940.Mos t of these bridges were designed for less traffic, smaller vehicles, slower and lighter loads than are presently found on the highway networks.In addition even for some newly constructed bridges,deterioration caused by service conditions and deferred maintenance is a growing problem.

2. BRIDGE DESIGN AND DISASTER ANALYSIS

The advances in bridge design techniques and innovative construction materials as well as rapidly increasing transport volume resulting in more "efficient" bridge structures may also introduce relatively more serious vibration of the bridges and increase potential damage. The Akashi Kaikyo Bridge in Kobe –Naruto, Japan with a main span of 1991m was opened to traffic in 1998.The Hum ber Bridge in the UK with a main span of 1410m had the longest single span in the world[1].and longer bridges are planned (e.g. Messina Straits(3300m),Gibraltar Straits(5000m)). These successes are due in particular to progress in wind-resistant design; a primary component in the design of longspan bridges. Recently, and driven by these advances, multi-m ode flutter and buffeting analysis procedures have been developed that complement the existing analytical approaches and fullbridge and taut-strip wind tunnel modeling. These procedures, which are based on frequency- domain methods, take into account the fully coupled aeroelastic and aerodynamic response of long-span bridges to wind excitation[2].

3. TYPES OF LOADING –WIND & EARTHQUAKE RESPONSE IN VERY LONG SPANCABLE-STAYED AND SUSPENSION BRIDGES

Very long span suspension bridges are flexible structural systems. The introduction of these cable suspended structures has been profoundly enhanced by t he development of new structural materials and computer methods of analysis. Cable suspended systems comprise both categories of suspension bridges and cable stayed bridges. These flexible systems are susceptible to the dynamic effects of wind and earthquake loads. Wind loads and earthquake loads make up what we call the lateral forces on a structure. A fundamental problem in dealing with these lateral forces is the computation of the magnitude of the wind load and the earthquake load. The structural effects, the response of the structure to such random lateral loads, and the subsequent design of an efficient lateral load resisting system, dictate very sophisticated methods of analysis and design. Such methods include but are not limited to classical methods of structural analysis, computer methods of structural analysis, experimental methods, as well as other validation and verification methods. The finite element methods present the engineer with a powerful structural analysis technology reliant on modern digital computers. Preprocessors and postprocessors are available to facilitate the input and output data of such advanced computers. The art in all this technology is to present the engineer with results that can predict reliably the response of such comp licated structural systems. Linear as well as nonlinear response, aerodynamic performance, structural stability, the choice of light materials for the superstructure, and other design considerations constitute the essence of the problem. Wind tunnels are available to help us understand the aerodynamic problem associated with the structural vibrations of long span suspension bridges subject to wind loads. Shaking table experiments also can help us understand the dynamic behavior of long span suspension systems. A structural designer is concerned with both aspects of strength and serviceability through out the expected service life of t he structure. The engineer needs a proper understanding of the following items to address this problem:

1. The structural system and its characteristics; 2. The nature of wind forces;
3. The nature of earthquake forces; 4. The computer modeling process,
5. The limitations of the commercial software utilized;
6. Wind tunnel experiments,
7. Shaking table instrumentation,
8. Reconci liation of the numerical and experimental results.

3.1 Suspension Bridges

Suspension bridges are a viable structural solution to spanning long distances. It is imperative that the cable system proposed would be capable of supporting its own weight in addition to the imposed loads of the superstructure. The weight of the cable is assumed to be distributed uniformly along the arc length of the cable. The choice of an optimum sag to span rat io is related to aesthetics as well as to aspects of minimizing the total weight of the main cable. The main structural elements of a suspension bridge are:

1. The main cable system,
2. The towers or pylons,
3. The anchorage,
4. The stiffening girder.

Very long suspension bridges require external anchorage to massive concrete foundations. This is called external anchorage. There are many studies that have shown that coupling of cable stays with a suspension system do not serve to reduce the deflections of the bridge structure.

The presence of these inclined cable stays serves the purpose of enhancing the torsional rigidity of the structure. Modern suspension bridges do not utilize cable stays in conjunction with a suspended system. However, there are bridges were such combination is displayed. n example of that is the San Marcos Bridge in El Salvador, with a system of inclined cable stays in the form of a network of cables. Such a concept is referred to as a cable-truss configuration. The Brooklyn Bridge, built by John Roebling, shows inclined cable stays in addition to the conventional suspension cable and hangar system. The German engineer Dischinger proposed t he addition of inclined cable stays to reduce the deflection suspension bridges. However as Leonhardt points out, such systems are not very effective in reducing the deformation of suspended systems. The current longest suspension bridge in the world is the Akashi-Kai kyo Bridge in Japan. This bridge is designed for an earthquake of magnitude 8.5 on the Richter scale and a wind speed of 80 miles per hour. The main span of this bridge is 6529 feet long. Almost all of the existing suspension and cable stayed bridges are made of structural steel cables. A recent development points out to the advantages of carbon-fiber-reinforced-plastic cables. These are superior t o steel cables when it comes to strength and corrosion resistance. Such composite cables provide the engineer with an equivalent elastic modulus comparable to that of steel cables. Current technology points out to the fact that for bridge systems of 1100 feet suspended span a cable stayed system provides the engineer with an optimal solution. For longer spans a suspension system should be considered. The cable stayed bridge system however, provides the engineer with additional stiffness since the cables are taut. This mechanism of prestressing the cables allows us to decrease the flexibility of a suspended span. This reduction in system flexibility reduces the vibrations of the bridge structure under the effects of wind loads. Gimsing, Menn, Mallick, Starossek, and others have addressed the problem of a very long span suspension bridge in the literature. There are proposed systems for very long span suspension bridges:

1. The hybrid cable stayed suspension bridge system,
2. The hybrid double cantilever suspension bridge system,
3. The Spread-Pylon cable stayed bridge system.

Very long span suspension bridges have been proposed by various consultants. One example is to connect the continent of Africa to Europe by a bridge that spans from Morocco to Spain. The proposed length of the bridge is 8.5 miles. A series of suspension bridges is considered for this design. Another proposed bridge is to connect Italy to the Island of Sicily. A great bridge is proposed to link the United States to Russia through the Bering Straits. The depth of the water at various points across the proposed path of the bridge present the engineer with technological hardships. Crossings beyond 10,000 feet require innovative technologies in materials and structural systems. As Menn points out, extrapolation of existing technologies does not present the engineering profession with innovative solutions.

3.2 Wind Effects on Suspension Bridges

Wind can produce the following effects on suspension bridges:
1. Wind lift and drag forces,
2. Aeroelastic effects (torsional divergence or lateral buckling),
3. Oscillations induced by vortex effects,
4. Flutter phenomena,
5. Galloping effects,
6. Buffeting caused by self-excited forces.

All of the above effects require wind tunnel tests. It is very important to understand here that studies are needed for the partially complete structure as well as the completed structure. The performance of the structure under the effect of wind loads should be investigated during the various construction stages of the suspension bridge. The construction period of large suspension bridges should be wisely planned for seasons where no serious storm conditions are anticipated. Proper prediction of the weather for extended time periods is important. If the construction is contemplated for seasons with predicted storm activities, energy dissipating devices and dampers should be used to reduce the magnitude of the vibrations on the partially completed structure. There are 3 types of wind tunnel tests on a suspension bridge:

1. Models of the entire bridge,
2. Taut strip models,
3. Sectional models.

The first category of wind tunnel models provides the engineer with the advantages of similitude between model and prototype. These models are expensive to build and constitute a large initial capital expenditure. Experience from previous designs indicates t hat a scale of 1 to 300 is desirable. Other scales are also possible. The distribution of the mass in such complete scale models is identical to the mass distribution of the real life structure or prototype. The second category, or the taut strip model, consists of 2 wires that are stretched across the wind tunnel. The response of such models to applied fluid flows in the wind tunnel is similar to the response of the center section of the suspension structure. The third category is made up of sections of the bridge deck in the span-wise direction. The ends of these sections are supported on spring type foundations to allow motion in the vertical direction as well as the rotational sense. The usual scales for such deck sections are within the 1/50 to 1/25 range. These sectional models are very important in determining the aeroelastic stability of the proposed deck system. These models all ow us to further investigate the steady state coefficients for drag, lift, and moment. These 3 quantities are fundamental characteristics of the suspension bridge deck. These coefficients are a function of the air density, the deck width of the bridge, the mean wind speed at the height of the deck, as well as the drag, lift, and moment per unit span length. The science of aerodynamics is very important here since various plots of these functions are usually done versus the angle of attack of the oncoming wind flow. It is also possible from a study of these sectional models to determine the aerodynamic coefficients attributed to the self-excited forces acting on the vibrating structure. Finally these models allow us the determination of a very important number in fluid mechanics, the Strouhal number. The Strouhal number is associated with vortex shedding. This non-dimensional number is defined as the product of the frequency of full cycles of vortex shedding and the dimension of the body projected on a plane perpendicular t o the mean velocity of the flow, divided by the velocity of the oncoming fluid flow. It is very important to note here that the fluid flow is presumed laminar in this formulation. The Reynolds number is very important in this type of analysis. Vortex shedding had been experimentally observed for cylinders and other bluff body shapes. Research continues on the topic of periodi c vortex shedding for very large Reynolds numbers [3].

4. BEHAVIOR OF BRIDGE CONSTRUCTION

Structures normally behave elastically which are designed to deform and reverse t o their original configuration. When a structure is loaded beyond its normal limits, it behaves plastically and becomes permanently deformed and weakened. Often this damage is invisible, but as strains in the structure increase and the structure edges closer to structural failure. For instances, changes in girder strains, joint rotations and crack growth are indicators for evaluating structural integrity. By monitoring such changes closely, it is possible to provide quantitative clarity to assess structural health. For long span bridges, such as, the world longest suspension bridge, Akashi Kaikyo Bridge, due to the bridge scale, its design adopted some newly developed design codes for aerodynamic, seismic stability and design constants. Some newly developed challenging technologies that have been applied in this super long bridge, such as, wind resistant design, seismic design, run ability of train on suspension bridge, large scale underwater foundation, working platform on the sea and seabed excavation method. The dynamic response against strong wind and earthquake are subjected to unknown factors those are uneasy to predict. Therefore, it is necessary to establish a monitoring system that can collect data on dynamic response of the bridge in order to verify the assumptions and constant used for the design due t o strong wind and earthquake. The wind load for long-span bridges has great importance in their structural design. It usually consists of time averaged wind force and some contribution of the dynamic response due to the wind fluctuation, but there still remain uncertainties in expression of wind characteristics to define the accurate and reliable wind load.

To overcome this it will be important to compile information of the wind at many bridge site. Here, as the example of monitoring result s, the deformation characteristics of t he bridge response due to typhoon are elucidated. By comparing the analyzed simulation results through wind tunnel test and field- measured results, the reliability of the current monitoring system is confirmed. Furthermore, by applying newly developed technology in intelligent material") (e.g., TRIP steels) and intelligent systems"), together with recent development of information and telecommunication infrastructure technology'), a better constructive monitoring system has been managed. Particularly, this new bridge management can include remote monitoring to obtain key information concerning bridge structural health, such as, water flow rates, relative motion, fatigue, and true-stress occurred in structure member t hat in an accumulated and combined way contribute to the damage profile of the structure. This proposed system is easily accessible, economically feasible and durable to provide information for structural health maintenance [4]. A suspension bridge usually characterizes two kinds of distinct deformations, i.e. the long-term movement caused by foundation settlement, bridge deck creep and stress relaxation, and the short-term dynamic motion of the bridge, such as those induced by wind, temperature, tidal current, earthquake, and traffic etc. Unlike the long-term bridge deformation, which is irrecoverable, the latter deformation is called a deflection since the deformable object will recover to its original status with the release of loadings, unless under an extreme loading, permanent damage or deformation is caused [8].

5. STRUCTURAL MONITORING OF BRIDGES DURING WHOLE LIFESPAN

Civil structures are omnipresent in every society, regardless of culture, religion, geographical location and economical development. It is difficult to imagine a society without buildings, roads, rails, bridges, tunnels, dams and power plants. Structures affect human, social, ecological, economical, cultural and aesthetic aspects of societies and associated activities contribute considerably to the gross internal product. Therefore good design, quality construction as well as durable and safe usage of civil structures are goals of structural engineering. The most safe and durable structures are usually structures that are well managed. Measurement and monitoring often have essential roles in management activities. The data resulting from the monitoring program is used to optimise the operation, maintenance, repair and replacing of the structure based on reliable and objective data. Detection of ongoing damage can be used to detect deviations from the design performance. Monitoring data can be integrated in structural management systems and increase the quality of decisions by providing reliable and unbiased information. Many structures are in much better condition than expected.

In these cases, monitoring allows to increase the safety margins without any intervention on t he structure. Taking advantage of better material properties, over design and synergetic effects, it is possible to ext end the lifetime or load-bearing capacity of structures. A small investment at the beginning of a project can lead to considerable savings by eliminating or reducing over-designed structural elements. Malfunctioning of civil structures often has serious consequences. The most serious is an accident involving human victims. Even when there is no loss of life, populations suffer if the infrastructure is partially or completely out of service. Collapse of certain structures, such as nuclear power plants, may provoke serious ecological pollution. The economic impact of structural deficiency is twofold: direct and indirect. The direct impact is reflected by the costs of reconstruction while the indirect impact involves losses in the other branches of theeconomy. Fully collapse of historical monuments, such as old stone bridges and cathedral s, represent an irretrievable cultural loss for society. Learning how a structure performs in real or laboratory conditions will help to design better structures for the future. This can lead to cheaper, safer and more durable structures with increased reliability and performance. Structural diversity due to factors such as geographical region, environmental influences, soil properties, loads etc. makes absolute behavioural knowledge impossible: there are not two identical structures. Structural monitoring represents a good way to enlarge knowledge of structural performance. In this paper, first an introduction to the monitoring process and concept of structural monitoring of concrete structures is presented. It includes notion of structural monitoring, presentation of principal of the monitoring systems and monitoring assessment.

5.1 Structural Monitoring Process

The monitoring process consists of the following activities:

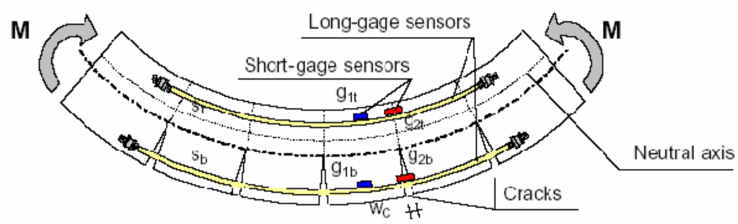
1. Selection of t he monitoring strategy
a. Identification of parameters to be monitored
b. Monitoring assessment and schedule
c. Selection of monitoring system or systems
d. Selection of sensor topology and network
2. Installation and maintenance of monitoring system
3. Collecting and storage of data
4. Data postprocessing (visualization, interpretation and analysis)

These activities are briefly presented in this section.
Selection of monitoring strategy 1: monitoring parameters, monitoring assessment and schedule
Monitoring (or auscultation) of structures involves recording of time dependent parameters during certain periods. To start a monitoring project, it is important t o define the goal of the monitoring i.e. to identify the parameters to be monitored, monitoring assessment and schedule. Monitored parameters can be physical, mechanical, chemical or other, and are usually present in each point of the structure. These parameters have to be properly selected in a way that they reflect the structural behavior. Each structure has its own particularities and consequent ly its own selection of parameters for monitoring. There are different approaches to assess the structure and we can classify them in three basic categories: static monitoring, dynamic monitoring, and system identification and modal analysis, and these categories can be combined. Each category is characterised by advantages and challenges and which one (or ones) will be used depends mainly on the structural behaviour and the goals of the monitoring. Each category can be performed during short and long periods, permanently (continuously) or periodically. The schedule and pace of monitoring depends on how fast the monitored parameters change in time. For some applications, periodical monitoring gives satisfactory results, but information which is not registered between two inspections is lost forever. Only continuous monitoring during the whole lifespan of the structure can register its history, help to understand its real behaviour and fully exploit the monitoring. The investment in the maintenance of the structure, using periodical inspections as a mean of control, can exceed the cost of a new structure.

5.2 Selection of Monitoring Strategy 2: Monitoring Systems and Structural Monitoring

The totality of means used for monitoring is called monitoring system. The main components of a monitoring system are sensors, carriers of information, reading unit, interfaces and data managing subsystems. The aim of the sensor is to detect the magnitude of the monitored parameter and to transform it to transportable information (e.g. optical of electrical information). The carrier leads the information from the sensor to the read ingunit, which decodes the information and retrieves the magnitude of the monitored parameter. The measurement is visualised and presented to the operator by a user interface. Finally, the data managing subsystem is necessary to control and manage the data obtained from monitoring.

The components of a moni toring system can be separated or differently combined (e.g. sensor and carrier can make one device). Monitored parameters can genrally be observed at material, structural or both material and structural level. Main difference between material and structural monitoring is in used monitoring strategy and monitoring system: material monitoring provides information related to material behaviour, but poor information concerning the structural behaviour; structural monitoring provides information related to structural behaviour. The difference between the material and structural monitoring is highlighted in Figure 2. In Figure 2, the strain monitoring of a bended concrete beam using four discrete short-gage sensors (g1t, g1b,g2t and g2b) and two long-gage sensors (st and sb) is presented (1). Al l sensors placed in the top of the beam (g1t, g2tand st) measure the same value, while the bottom sensors (g1b, g2b and sb) measure different values, due to the crack openings. Short-gage sensors (g1b and g2b) are highly influenced by crack presence and they provide information related only to their locations in the beam. The long-gage sensor (sb) measures an average value of the strain combined with the crack openings, which is related to the structural behaviour. E.g. it is possible to determine structural behaviour of the beam by calculating its curvature as ratio between measurement difference and distance between sensors (2). There is no simple technique that allows determination of structural behaviour using results obtained from short-gage sensors. Hence, for the monitoring strategy presented in Figure 2, long-gage sensors allow monitoring at structural level, while the short-gage sensors allow monitoring on material level while the short-gage sensors allow monitoring on material level.



5.3 Installation of Monitoring System

The installation of the monitoring system is a delicate phase. Therefore it must be planned in details considering seriously on-site conditions and notably the structural component assembling activities, sequences and schedules. Main principles and issues met during the installation are briefly cited in this subsection. The components of the monitoring system can be embedded into the fresh concrete or installed on the structure surface using fastenings, clamps or gluing. In both cases the installation of the monitoring system can annihilate the structure (e.g. embedded sensors reduce area of the cross-section, to set the connection boxes or extension cables on surface it is necessary to drill the holes and to install fastenings, etc.). Therefore, it is important to ensure that, from the structural and aestetichal point of view it is possible to install the system, and that the presence of the monitoring system as well as the installation works will not decrease the performance of the structure. The installation takes time, and if it is to be performed during the construction of t he structure, it may delay the works. Components of monitoring system t hat are to be installed by embedding can only be safely installed during a short period between the rebars completion and pouring of concrete. Hence, the schedule of installation of the monitoring system has to be carfully planed taking into account the schedule of works, ti me necessary for the system installation, but in the same time it has to be flexible in order to adapt to work schedule changes that are frequent in building sites. When installed, the monitoring system has to be protected, notably if monitoring is performed during the construction of the structure. The protection has to prevent accidental damage during the construction but also to ensure the longevity of the system. Thus, all external influences, periodical or permanent, such as vandalism, rodents (or other animals), wind, rain, sun etc. has to be taken into account when designing the protection for the monitoring system.

5.4 Collecting and Storage of Data

The monitoring data can be collected manually or automatically, on-site or remotely, with or withour human intervention, periodically or continuously. These options can be combined in different way, e.g. for example during the test of the bridge it is necessary to perform measurements automatically, on-site, with human intrvention and periodically (after each load step). For long-term in use monitoring the maximal performance is automatic, remote (from the office), continuous collecting of data without human intervention. Data can be stored in form of reports, tables, diagrams etc. on different types of supports such as electronic files (on hard disc, CD, etc.) or hard versions (printed on paper). The manner of storage of data has to ensure that data will not be lost and that a prompt access to any selected data is possible (e.g. one can be interest ed to access only data from one group of sensors and during a selected period of monitoring). The software that manage the collecting and storage of data are to be a part of the monitoring system. Otherwise, the data management can be difficult, demanding and expensive.

5.5 Data Post-processing

Data postprocessing consists of interpretation, visualization and analysis. Collected data is in fact huge amount of numbers (dates and magnitudes of monitoring parameters), and has to be transformed to usefull information concerning the structural beavior. This transformation depends on monitoring strategy and algorithms that are used to interpret and analyse the data. It can be performed manually, semi-automatically or automatically. Manual data postprocessing understands manual export and analysis of data. It is practical in cases where the amount of data is limited. Semi-automatic postprocessing cosisists of manual export of data and automatic analysis using the softwares. It is applicable in cases where the data analysis is to performed only periodically. Finaly automatic postprocessing is the most convenient, since it can be performed rapidly and indepndent of data amount or frequency of analysis. The data postprocessing has to be planned along with selection of monitoring strategy and appropriate algorithms and tools compatible with the choosen monitoring system have to be selected.

5.6 Whole Lifespan Monitoring of Bridges

5.6.1 Monitoring during construction of a new bridge

Construction is a very delicate phase in the life of structures. For concrete structures, material properties change through ageing. It is important to know whether or not the required values are achieved and maintained. Defects (e.g. premature cracking) that arise during construction may have serious consequences on structural performance. Monitoring data help engineers to understand the real behaviour of the structure and this leads to better estimates the real performance and al low more appropriate remedial actions. Important information obtained through the monitoring during construction includes the following: Estimation of hardening time of concrete in order to estimate when shrinkage stresses begin to be generated; Deformation measurements during early age of concrete in order to estimate self-stressing and risk of premature cracking; When structures are constructed i n successive phases, measurement can help to improve the composition of concrete when necessary. In case of pre-fabricated structures, sensors may be useful for quality control; Optimisation between two successive phases of pouring due to evaluation of cure in previous phases; For prestressed structure, deformation monitoring of cables helps t o adjust prestressing forces and determine the relaxation; Monitoring of foundation settlement helps to understand the origins of built-in stresses; Damage caused by unusual loads such as thunderstorm or earthquakes during construction may influence the ultimate performance of structures; Optimal regulation of structural position during erect ion; Knowledge improvement and recalibration of models. The installation of a monitoring system during the construction phases al lows monitoring to be carried out during the whole life of the structure. Since most structures have to be inspected several times during service, the best way to decrease the costs of monitoring and inspection is to install the monitoring system from the beginning. Monitoring after refurbishing, strengthening or enlargement of bridge Material degradation and/or damage are often the reasons for refurbishing existing structures. Al so, new functional requirements for the bridge (e.g. enlarging) lead to requirements for strengthening. If strengthening elements are made of new concrete, a good interaction of new concrete with the existing structure has to be assured. Early age deformation of new concrete creates built-in stresses and bad cohesion causes delamination of t he new concrete, thereby erasing the beneficial effects of the repair or strengthening efforts. Since new concrete elements observed separately represent new structures, the reasons for monitoring them are the same as for new structures, presented in the previous subsection. The determination of the success of refurbishment or strengthening is an additional justification.

5.6.2 Monitoring during testing of bridge

Bridges have to be tested before service for safety reasons. At this stage, the required performance levels of structures have to be reached. Typical monitored parameters (such as deformation, strain, displacement, rotation of section and cracks opening) are measured. Tests are performed in order to understand the real behaviour of the structure and to compare it with theoretical predictions. Monitoring during this phase can be used to calibrate numerical models describing the behaviour of structures.

5.6.3 Monitoring during service of bridge

The service phase is the most important period in the life of a structure. During this phase, construction materials are subject to degradation by ageing. Concrete cracks and creeps, steel oxidises and may crack due to fatigue loading. The degradation of materials is caused by mechanical (loads higher then theoretically assumed) and physicochemical factors (corrosion of steel, penetration of salts and chlorides in concrete, freezing of concrete etc.). As a consequence of material degradation, the capacity, durability and safety of structure decrease. Monitoring during service provides information on structural behaviour under predicted loads, and also registers the effects of unpredicted overloading. Data obtained by monitoring are useful for damage detection, evaluation of safety and determination of the residual capacity of structures. Early damage detection is particularly important because it leads to appropriate and timely interventions. If the damage is not detected, it continues to propagate and the structure no longer guarantees required performance levels. Late detection of damage results in either very elevated refurbishment costs (5) or, in some cases, the structure has to be closed and dismantled. In seismic areas the importance of monitoring is most critical. Subsequent auscultation of a structure that has not been monitored during its construction can serve as a basis for understanding the present and for predicting the future structural behaviour. This is discussed next.

5.6.4 Monitoring during dismantling of bridge

When the structure does no longer respond to the required performances and the costs of reparation or strengthening are excessively high, the ultimate life-span of the structure is attained and the structure should be dismantled. Monitoring helps to dismantle structures safely and successfully[5].

5. IMPOTANCE OF MONITORING OF BRIDGE CONSTRUCTION

The security of bridges requires periodic monitoring, maintenance and restoration. Excessive and non-stabilized deformations are often observed and although they rarely affect the global structural security, they can lead to serviceability deficiencies. Furthermore, accurate knowledge of the behavior of bridges is becoming more important as new structures become lighter and as and increasing number of existing bridges are required to remain in service beyond their theoretical service lives. Monitoring, both in t he long and short term, helps to increase the knowledge of the real behavior of the bridge and in the planning of maintenance intervention. In the long term, the static monitoring needs of an accurate and very stable system able to relate deformation measurements often spaced over long periods of time. On the other side, dynamic analysis of bridges, or short term monitoring, requires of a system capable of measuring deformations occurring over relatively short periods of time. Currently available monitoring transducers, such as inductive and mechanical extensometers, GPS, microbending sensors or accelerometers are only suitable for performing measurements in a short range of frequencies. Moreover some of these techniques are still in the development stage and only used in laboratory experiments (for example, GPS).Other systems do not offer enough information about the desired parameter (for example, accelerometers give us the frequency of vibration, but displacements calculations are not accurate). Thus, there is a real need of a unique sensor capable of covering structural deformation requirements in wide range of frequencies[6].

5.1 Why Permanent Monitoring is Necessary ?

Bridge spatial displacement is a factor relatively facile to measure for short term condition but difficult for long term monitoring. In fact, it is generally not possible to put mechanical gauges in permanence under a bridge or place a geometer measuring every hours by optical levelling process. Permanent monitoring is necessary to compare the spatial displacement due to non-temperature effect. In fact, effect on bridge are due to 5 causes:

1- permanent load (for example the weight)
2- static and variable load (traffic load, wind load…)
3- thermal effect
4- evolution of the material proprieties (shri nkage, creep…)
5- disaster in the bridge (crack, support settlement…)[7].

6. GPS AND ITS APPLICATIONS

The Global Positioning System (GPS) has been used for many years for the deformation monitoringof man-made structures such as bridges, dams and buildings, both for long-term deformations as well as instantaneous deflections[8,9]. In these applications,uniform three-dimensional positioning precision in a local coordinate system is required.Some of these applications have specific precision requirements in the vertical direction, for example when analyzing land subsidence, while others are concerned with the north or east direction such as evaluating the structural deformations caused by wind loading. It is important to analyze the achievable positioning precision with the current GPS constellation and potential augmentation techniques for such engineering applications [10]. GPS technology is widely used in navigation.[11].It can provide position information with accuracy to a few millimeters in near real-time. Thanks to this level of precision, the movement of large structures can be monitored accurately [12].

7. GPS FOR STRUCTURAL MONITORING

Recent advances in GPS technology and data processing software have made GPS a much more convenient ,accurate and cost-effective tool for natural and man-made structural deformation monitoring .The Geographical Survey Institute(GSI)network in Japan which covers the territory of Japan with GPS station intervals of about 10~15 km and the Southern

California Integrated GPS Network (SCIGN)are two typical examples of large scale ,permanent GPS networks for conducting near or real-time crustal motion monitoring .For example Ashkenazi et al.[1998]present an example of GPS –based vertical land movement monitoring for selected sites reciever technology enables L-band phase measurments to be made with a resolution of much less than 1mm level [Cross,2000],GPS is increasingly used to monitor engineering structures such as bridges ,dams, offshore plateforms, etc[Rizos et al.,1997].Using state-of-the art dual frequency GPS recievers, UHF data links(technology) and high-speed portable processors allows real-time processing and navigation t o centimetre kinematic positioning mode. With the pure GPS techniques, it will be very difficult to monitor the quality of the observations, articulary with loss of satellite signals in difficult observation environments are common lessons learnt from GPS kinematic surveying ,and will introduce new ambiguities to the solution. Ignal re-capturing normally takes time, depending on the reciever quality and observation condition, and will cause discontinuous observations. Relatively low dat a rate (max 20HZ currently)coul d not satisfy the requirement to monitor higher structural dynamics (Nyquist frequency >10HZ).A Nyquist frequency of higher rat e than this would not be detectable by GPS alone. There are two system architectures for structural monitoring with GPS, one based on a fixed network of sensors and the other based on mobile sensors. The following sections describe these two implementations and discuss how recent advances in GPS receiver technology are making such systems cost-effective[13]. Structural monitoring serves several purposes. For example, it can provide structural response data allowing for the as-built performance to be checked against design criteria, which will be an increasingly useful exercise given the move towards 'performance based design' of structures. Over along period monitoring can also provide the opportunity to identify 'anomalies' that may signal unusual loading conditions or modified structural behaviour, which can, in the extreme case, include damage of failure. A final use is to provide data for calibrating design codes. The performance of the building has already been checked against the design, and a complete understanding of the way the structure behaves has been obtained (Brownjohn et al, 2000; Brownjohn & Pan, 2001). Procedures are currently being developed to detect anomalies, however in this case perhaps the major value of this exercise is for the calibration of local design codes[14].

8. TRADITIONAL MONITORING TECHNIQUES FOR SURVEYING DISPLACEMENT OF BRIDGE

There are some conventional methods for measuring structural vibration or displacement .These methods include measurement with accelerometer, measurement with a laser interferometer and measurement with an electronic distance measurement instrument (Lovse,1996).Accelerometer measurement is the standard method of measuring st ructural vi bration. It is very light, small size and thus have a minimal effect on the properties of the vibrating system.But it requires direct contact of the sensors with the structure, and wiring is also required tolink the accelerometers to a central recording unit. The wi ring can easily be damaged.Accelerometer cannot measure the swing of total vibration of structure because accelerationcannot be obtained well and truly when structure moves slowly.The measurement of laser interferometer is used to measure the changes in distance between the interest point and t he reference point by using laser interferometer. A prism or reflective film must be mounted at the point of interest. The distance change versus time can be collected and be further analyzed to determine dominant frequencies and corresponding amplitudes. This method has the advantage of high accuracy, but it is difficult to catch the measure point when the shake or vibration of structures is too big. Electronic distance measurement is similar the laser interferometer method. It can be carried out with much less expensive equipment. But the resolution of the changes in distance and the sampling rate are much lower than for a laser interferometer. For one electronic distance measurement instruments with a sampling rate of c Hz, it can only be used t o collect the information wit h frequency of less than 0.5c Hz Laser interferometer and electronic distance measurement instrument are limited by climate condition, i.e. clear line of sight is the basic condition in which they can work. In addition, they have some disadvantages, such as the measurements in different interest points are not synchronous, it is difficult to measure the bigger displacement, and it is difficult to get the observations in real time. In a word, all these traditional methods are limited, and not satisfied to the demands of monitoring dynamically large structures in the aspects of continuity, realtime and automatization[14].Traditional monitoring techniques foresee measurement campaigns at regular interval s(usually months) and work by determining angles and distances between points using optical instruments as theodolites or distance meters. The achievable level of precision with these instruments is generally very high. three important disadvantages of Traditional monitoring techniques are:

1- The first is that precision of traditional optical methods is heavily dependent on environmental and meteorological conditions (day/night, temperature, pressure, rain and fog).
2- The second concerns intervisibility and distance between measured points. With traditional methods these are fundamental requirements, but with GPS-based measuring methods these are by no means relevant issues.
3- The third has to do with the difficulties inherent in setting up traditional equipment for unattended automatic operation over extended periods of time, brought about by t he high cost of the equipment as well as the limited suitability for outdoors
Operation [12].

9. PRINCIPLES OF USING GPS IN SURVEYING DISPLACEMENT OF BRIDGE

Due to the severe conditions encountered in the bridge deflection monitoring environment,the equipment used must be lightweight,portable,reliabl e,easy to apply,and results must be easy to interpret. Conventional surveying methods such as leveling have been used in the past to monitor static displacements of engineered structures and will surely continue to be used for many years. But the inherent disadvantages of traditional systems like surveying robots, theodolites and leveling instruments or terrestrial photogrammetry have greatly limited their application fields. Because of the limitations of traditional surveying methods, they have very limited importance for high dynamic structural deflection monitoring. Al though accelerometers, tiltmeters,and strain gauges are used to provide deflection and displacement measurements in the bridge inspection, there are also some inherent limitations in these approaches. Except for the equipment cost, these sensors must be installed, maintained and frequently recalibrated. The collected raw data need to be interpreted to obtain direct geometric results,which i n many cases is compli cated procedure. Furthermore,conventional survey methods require a "line of sight" and do not lend themselves as well as GPS to unattended, continuous field operations utilizing high sampling rates and integrated network communications techniques. While data reduction is less complex for conventional surveying systems than for GPS, robust automation of highly precise GPS data analyses is now reasonably routine. Conventional surveying instruments are also limited in range and do not offer connection to an absolute reference frame, as does GPS. This has made it exceedingly difficult to assess how the structures might have moved with respect to surrounding bedrock after an earthquake or disastrous wind attack or tidal current. Hyzak et al [1997] summarised some main reasons that GPS surveying has found applications for structural deflection monitoring. These are mainly because GPS surveying could supply

(1) all weather observations;
(2) changeable accuracies of 1 cm (instantaneous) to 1 mm (with averaging) which makes GPS suitable for different application scenarios;
(3) 3D positions in an uniformly established world reference (WGS 84);
(4) continuous monitoring with data rates up to 20 Hz;
(5) automated operation with less human intervention, near real time capability;
(6) kinematic methods for efficient data collection;

In addition, the distance between the user on the land and the sensor on the bridge can be up to ~20 km. On the other hand, GPS observations can serve as the spatial frame for the other kinds of physical observations such as those from accelerometers and strain gauges and be integrated into a totally automated and continuously operating system [Brown, et al., 1999]. A GPS system that could detect large-scale deflections that exceed design predictions would be useful in that it might indicate that bridge components require immediate inspection or maintenance. In addition, if under unusual loading, such as wind loading (tropical storm, hurricane etc) that create large displacements, a GPS system could give a real-time warning that the bridge should be inspected or even closed to minimise safety risks. GPS has been gradually replacing other traditional bridge inspection instruments and is becoming an important and useful tool of NDE. level. A series of trials to monitor the movement of suspension bridges is described in Ashkenazi et al. [1997], Roberts [1997], Young [1998] and Roberts, et al. [1999a]. The deflections of a suspension bridge of up to a few decimetres under extreme traffic loads is reported. The use of kinematic GPS positioning at strategic points upon the bridge decks also allows close monitoring of the bridge‘s dynamic responses [Brown et al., 1999]. Such real-time monitoring can be used to warn of potentially dangerous bridge movements and calculate instant deformation and long-term deterioration factors for the bridge. Moreover, future bridge designs and traffic management schemes could benefit from such a deformation monitoring system[1].The carrier phase double difference mathematic model is adopted to survey the structures with GPS. This model can remove the error between the clocks in the satellite and the receiver. The errors of satellite orbit and atmosphere can be reduced by kinematic GPS positioning with instantaneous cycle ambiguity resolution of On-the-Fly. Because the errors of orbit and atmosphere are connected with the distance between the datum point and monitoring point, a GPS receiver antenna should be placed near t o the target bridge as a datum station.

This point should be stable, and there are no buildings above 50 to envelop or reflect signals. Another GPS receiver antenna should be placed on the monitoring point, which is often at the mid-span, quarter span or the top of towers. And t here had better be no structures to envelop the signal, either. At lease 5 satellites signal should be received at the same time, and the data will be stored in the computer real-time. The datum point and monitoring point record 15~20 min data synchronously, which is call a monitoring stage. In data processing, data of the former 200s, just about 3 minutes, are used to obtain the instantaneous cycle ambiguity resolution. When the ambiguity WGS- 84 geodetic coordination. And the horizontal and vertical displacement of bridges can be computed by coordinate projection and translation. The main vibration frequencies and vibration amplitudes can be determined by spectrum analysis with fast fourier transform algorithm method (FFT), too [14].

9.1 GPS Errors and Accuracy'

Al though GPS is clearly the most accurate worldwide navigation system yet developed, it exhibits more or less significant errors. The accuracy of GPS results depends upon many heterogeneous factors in relation to purpose of the measurements, GPS observation method, instrumentation, conditions in situ, satellite constellation, and processing technology. In engineering applications mostly phase data are used. The baselines between a reference and rover stations are computed with help of single, double, or triple differences of phase measurements. Many systematic influences are eliminated in this way. Longer observation intervals eliminate most of the periodical errors. Another possibility (like in classical geodetic methods) is to repeat the measurements in different time, and in different observation conditions. Greater t he time span of observations, higher the variations, but better the real accuracy with smaller correlations in the output parameters. Important for a surveyor is to do proper error pre-analysis concerning the surveying method employed. For the purpose it is necessary to know about real accuracy limits, so as to choose technically and economically optimal measuring technology. The accuracies of GPS measurements depend mainly upon system and instrumental errors, both random and systematic. Most dangerous are the systematic biases which affect the results external accuracy. Particular GPS error sources and ways of elimination are described f.e. in (Teunissen, Kleusberg 1998).Processing stage is also important - the proper processing procedure (strategy) must account for most of the biases. Problematic are the covariance matrices of processing results which are underscaled (and therefore not realistic) in most cases. An experience is that the relative information in covariance matrices is more reliable than t he scale. That often makes problems in weighting of observations in adjustment, especially if different sessions or GPS and classical measurements are combined.

There are three elementary ways to more informative accuracy evaluations: the comparison of session results (preferably sessions of different days), the comparisons of GPS result s vs.„ground truth“ (well determined station positions), and the results comparison of GPS and other (classical) geodetic measuring methods. In present time the data and products of the International GPS Service (IGS) are available. There are two main contributions of permanent stations data. First is the provision of good quality data which can be used for computation of more reliable ionosphere model. Second is t he possibility to include the permanent station into the network structure, with gains of easy maintaining a consistent reference frame f.e. for long term monitoring of structures. It may also reduce the survey costs. In near future there will be even the possibility to use data from some permanent stations in real time applications. Some experiments concerning the permanent station TUBO situated at Brno University of Technology were carried out. The products of IGS (precise satellite orbits, clocks) are nowadays of high precision and may be contributing to better accuracy in some cases [19].Factors that can degrade the GPS signal and thus affect accuracy include the following:

9-1-1- Ionosphere and troposphere delays — The satellite signal slows as it passes through the atmosphere. The GPS system uses a built-in model that calculates an average amount of delay to partially correct for this type of error.
9-1-2-Signal multipath — This occurs when the GPS signal is reflected off objects such as tall buildings or large rock surfaces before it reaches the receiver. This increases the travel time of the signal, thereby causing errors.
9-1-3-Receiver clock errors — A receiver's built-in clock is not as accurate as the atomic clocks onboard the GPS satellites. Therefore, it may have very slight timing errors.
9-1-4- Orbital errors — Also known as ephemeris errors, these are inaccuracies of the satellite's reported location.
9-1-5- Number of satellites visible — The more satellites a GPS receiver can "see," the better the accuracy. Buildings, terrain, electronic interference, or sometimes even dense foliage can block signal reception, causing position errors or possibly no position reading at all. GPS units typically will not work indoors, underwater or underground.
9-1-6-Satellite geometry/shading — This refers to the relative position of the satellites at any given time. Ideal satellite geometry exists when the satellites are located at wide angles relative to each other. Poor geometry results when the satellites are located in a line or in a tight grouping.
9-1-7-Intentional degradation of the satellite signal — Selective Availability (SA) is an intentional degradation of the signal once imposed by the U.S. Department of Defense. SA was intended to prevent military adversaries from using the highl y accurate GPS signals. The government turned off SA in May 2000, which significantly improved the accuracy of ci vilian GPS receivers[20].

9.1.1 Ionospheric Corrections

The ionosphere is a band of the Earth’s upper atmosphere located approximately 50km–1000km above t he surface. The high spatial and temporal variability of the ionosphere has a major effect on GPS signals travelling from the satellite to the receiver. Moreover, the condition of the ionosphere is strongly related to the 11-year sunspot activity cycle. The most recent solar maximum occurred in 2000-2001, causing high ionospheric activity and having a clear impact on the results presented in this paper. It is well known that the ionosphere is most active in a band extending up to about 20° on either side of the geomagnetic equator. This is also one of the two regions where small scale ionospheric disturbances (short-term signal variations in amplitude and phase known as scintillations) mainly occur. The other being the high-latitude region close to the poles. In the equatorial region scintillations occur between approximately one hour after sunset until midnight (Klobuchar, 1996), and should have disappeared by 3am local time (IPS, 2002). The occurrence of scintillations also varies with the seasons. Between April and August they are less severe in the American, African and Indian longitude regions, while they are at a maximum in the Pacific region. The situation is reversed from September to March (Seeber,1993). In mid-latitudes scintillations are rarely experienced, but Medium-Scale Travelling Ionospheric Disturbances(MSTIDs) occur frequently, mainly during daytime in the winter months, during periods of high solar activity, with a maximum around local noon (Wanninger, 1999).While data from dual-frequency GPS receivers can account for the ionospheric delay directly by the appropriate linear combination of measurements made on both frequencies, data from single-frequency receivers cannot be corrected in this way. A simple ionosphere model transmitted within the navigation message can be used to account for about 50% of the ionospheric range delay on L1 (Klobuchar, 1987). However, this is not sufficient for deformation monitoring applications where it is desired to detect movement s of a few centimetres or less. For deformation monitoring a mixed-mode GPS network approach can be adopted, where a fiducial network of dual frequency receivers surrounding the deformation zone can be used to generate ‘correction terms’. These can then be applied to the single-frequency observations to account for the ionospheric effects and hence improve baseline accuracy. Figure 1 shows the ideal configuration of such a mixed-mode GPS network where the triangles denote fiducial stations, while the dots indicate single-frequency sites. The reference stations are to be situated outside the deformation zone but within the local tectonic region in order t o avoid unwanted displacements of the external network. Ideal network configuration of a mixed-mode GPS deformation monitoring network Han & Rizos (1996) and Han (1997) have proposed a linear combination model, which utilises a single ionospheric layer model at a height of 350km. This approach can account for orbit bias and ionospheric delay, as well as mitigate tropospheric delay, multipath and measurement noise across t he network. Data from t he GPS reference station network can be used to derive empirical corrections to the double differenced carrier phase data formed between the stations of the inner network[21].

9.1.2 Tropospheric errors

The tropospheric propagation delay is caused by the lower atmosphere and includes, in reality, not only delays in the troposphere, but also delays in the stratosphere, mesosphere and thermosphere and should, more correctly, be designated the neutral atmosphere delay. However, as it is the troposphere which induces the largest delays, it is just known as tropospheric error. Generally, this error is decomposed into two components: - a dry component, which is a function of surface pressure and temperature and accounts for about 80% to 90% of the total delay; a wet component, which is a function of the distribution of water vapour and is, therefore, harder to model, despite being responsible for only 10% to 20 % of the delay. In terms of time decorrelation of this error, what counts is not the difficulty to model each component but their variability, which is mainly diurnal, especially temperature and humidity variations. However, the full 24-hour variations of the meteorological parameters are “very small (…)because of the nearly constant ratio of constituents of the air, wit h the exception of water vapour and condensed water” [Reference 3], which nevertheless account for a very low percentage of the delay. Therefore, this error does not suffer significant variations in timescales of a few minutes and, besides being almost entirely removed by the differential technique, has an almost negligible decorrelation with time (when considering the DGPS error budget)

9.1.3 Satellite clock errors

Satellite clock errors are due to differences between the satellite clock time and that predicted by The satellite data. These differences are usually accepted to be about 5 ns [Reference 1], resulting in Pseudo-Range errors of 1.5 m. The oscillator that times the satellite signal is freerunning and is monitored by the GPS Control Segment stations, which establish corrections that are sent up to the satellite to set the data message. The user reads the data and adjusts the signal timing accordingly. As long as both Reference Station and user receivers are employing the same navigation message data, satellite clock errors are completely compensated by the differential technique. To achieve this, the Reference Station broadcasts a word – named Issue Of Dat a (IOD) – which indicates the reference time of the ephemeris and clock parameters used at the Reference Station. “The IOD is the key to ensure that the user equipment calculations and Reference Station corrections are based on the same set of broadcast orbital and clock parameters”. This word is included in messages RTCM SC-104 type 1 and 9, so that the DGPS user equipment may compare it with the IOD of the navigation message being used. For low age corrections, satellite clock errors are entirely compensated by DGPS and – as the drift of the satellites clocks is very slow – the corresponding decorrelation with time is almost negligible.

9.1.4 Satellite ephemeris errors

Satellite ephemeris errors are due to differences between the actual sat ellite location and the predicted location using the satellite orbital data. These differences are generally small (in the order of2 m) [Reference 1] representing a positioning error to the GPS user of a few decimetres.Ephemeris errors are almost completely compensated by the differential technique as long as both Reference Station and user receivers employ t he same satellite data, which is ensured by the IOD, broadcast by the Reference Station. These errors are very slowly changing and, hence,strongly correlated over many minutes[21].

9.2 Coordinate Transformation and Attitude Determination for the Bridge Deck

In the context of bridge deflection monitoring , as illustrat above,the main movement is in the vertical direction due to traffic loading in the most case. when wind loading is added, the lateral movement might increase depending on degree of wind intensity. The azimuth of bridge axis is constant in the WGS84 reference frame after bridge construction and it can also be calculated from the measurement from two adjacent GPS sites. when the bridge is in the quasistic mode(with less traffic),the pitch and roll are very small with even smaller changes over time and the modulus of t he acceleration vector measured with triaxial accelerometer equals 1g.two adjacent GPS sites along the same bridge handrail, simultaneously gathering data, are used for calculating pitch and yaw and two GPS sites simultaneously gathering data on opposite sides of bridge deck are used to calculate roll.

$$roll = \phi = \frac{H_{site2} - H_{site1}}{\sqrt{\left(\Delta X^2\right)_{site1/2,3} + \left(\Delta Y^2\right)_{site1/2,3} + \left(\Delta H^2\right)_{site1/2,3}}} = \frac{\Delta H}{d}$$

$$pitch = \theta = \frac{\Delta H}{\Delta Y} = \frac{H_{Site2} - H_{Site1}}{Y_{Site2} - Y_{Site1}}$$

$$yaw = \Psi = \frac{\Delta X}{\Delta Y} = \frac{X_{Site2} - X_{Site1}}{Y_{Site2} - Y_{Site1}}$$

$$\begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$$

$$a_{21} = -\sin(\varphi)\cos(\phi) + \cos(\varphi)\sin(\theta)\sin(\varphi) \qquad a_{11} = \cos(\varphi)\cos(\theta)$$

$$a_{22} = \cos(\Psi)\cos(\phi) + \sin(\Psi)\sin(\theta)\sin(\phi) \qquad a_{12} = \sin(\varphi)\cos(\theta)$$

$$a_{23} = \cos(\theta)\sin(\phi) \qquad a_{13} = -\sin(\theta)$$

$$a_{31} = \sin(\psi)\sin(\phi) + \cos(\psi)\sin(\theta)\cos(\phi)$$

$$a_{32} = -\cos(\psi)\sin(\phi) + \sin(\psi)\sin(\theta)\cos(\phi)$$

$$a_{33} = \cos(\theta)\cos(\phi)$$

10. PRINCIPLES OF USING TRIAXIAL ACCELEROMETERS IN SURVEYING DISPLACEMENT OF BRIDGE

Accelerometers have been used extensively for bridge dynamic monitoring using the force measurements directly. These sensors are used ti sense accelerations, and triaxial accelerometers could measure three orthogonal accelerations simultaneously. Compared with other surveying systems such as a surveying total station,triaxial accelerometers have some special advantages when they are used for bridge monitoring .The sampling rate of an accelerometers can reach several hundred Hz or even higher depending upon application requirements, which is a very important characteristic w hen monitoring a bridge with high dynamics. Triaxial accelerometers also superior to other sensors since they are not dependent on the propagation of electromagnetic waves, and therefore avoid the problems of signal refraction, line of sight connections to the terrestrial or space objects ,and do not have the visibility problems caused by the weather conditions. An accelerometer could form a completely self-contained system, utilizing only measurements of accelerations to infer the positions of the system, throught integration based on the laws of motion. However, the drift caused by the instrumental biases and scale factor offsets can develop very fast over time. Hence, accelerometer can not work alone to drive positioning solutions for a long period .Since the accelerometers are sensible to detect structures vibration w ith high frequencies, it has difficuly to sense very slow vibration w ith large deformation amplitudes accurately .In summary, either GPS or accelerometer alone can not provide deformation monitoring measurements which can be used to detect deformation and extract vibration frequencies of the monitored structures[28].

11. GPS AND TRIAXIAL ACCELEROMETER INTEGRATION

To avoid relative movement of the sensors in order to simplify the GPS and triaxial accelerometer data integration and to reduce the complexity of the data processing algorithm, the two kinds of sensors should be seamlessly fixed together. At the same time one axis of the triaxial accelerometer should be aligned with a known direction, usually the bridge's main axis (normally in the longitudinal axis direction). All the measurements are then transformed into a uniform coordinate system. A Software package developed at the IESSG can be used to synchronise the time series from the sensors. To meet the above requirements, a specially designed device is used to mount the GPS antenna and triaxial accelerometer (Figure 1a, 1b).

This device consists of two rotatable plates connected with three bolts. The GPS antenna is mounted on the upper plate which can be orientated to north. The triaxial accelerometer is fixed on the second plate with four screws. Its physical centre B coincides with the plate centre and one axis locates on the straight line marked by A and C. The whole device can be installed onto any standard tribrach. When the tribrach is properly levelled, the centre of the GPS antenna, the physical centre of the accelerometer and the centre of the tribrach's base are situated into the same vertical axis. Through levelling and rotation, the body frame of the triaxial accelerometer can be aligned with the bridge's axis. In practical use, a U-shaped clamp with centring bolt on top is used to fix the device on the bridge's handrail (Figure 1c). Figure 2 shows the accelerometer alignment procedure. A theodolite is placed upon the handrail of the bridge, and used to define the bridge's longitudinal axis through targeting the centre bolt of the middle span tribrach. The first plate of the housing device is rotated until markers A and C (Figure 1a) are oriented along the bridge's axis. The antenna is orientated to north at the same time. To determine the estimates of pitch and roll, an accelerometer threshold is applied to identify quasi-static moment. The threshold can be obtained through lab tests before conducting real-life data acquisition. When the accelerometer measurements are larger than the threshold it indicates that there are external accelerations acting on the accelerometer . When the accelerometer is in the quasi-static mode , the following formula can be used to solve the pitch and roll unknowns.

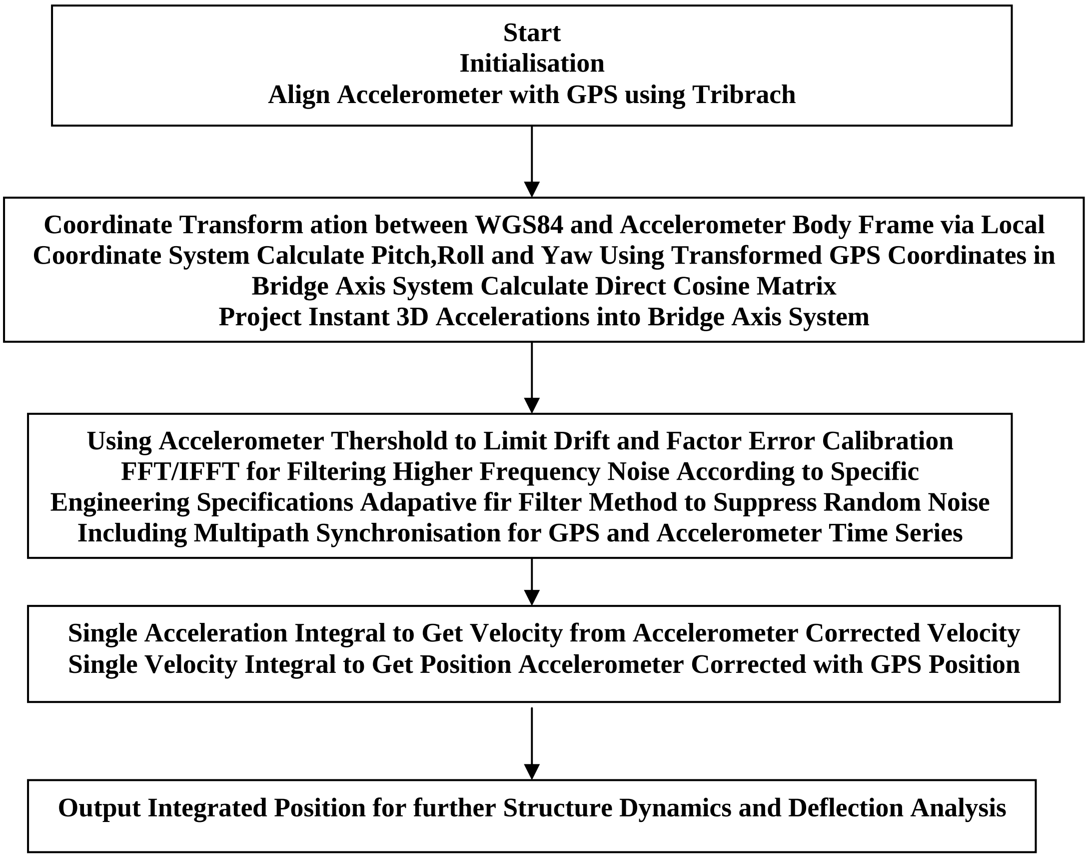
$$\begin{bmatrix} \hat{f}_x \\ \hat{f}_y \\ \hat{f}_z \end{bmatrix} = -R_{bToG} \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} = \begin{bmatrix} Sin(\theta)g \\ -Cos(\theta)Sin(\phi)g \\ -Cos(\theta)Cos(\phi)g \end{bmatrix}$$

Which can be solved for θ and ϕ as [Farrell and barth 1998]

$$\begin{bmatrix} \hat{\theta} \\ \hat{\phi} \end{bmatrix} = \begin{bmatrix} Arc\ \tan\ 2(-\hat{f}_y, \hat{f}_z) \\ Arc\ \tan\ 2(\hat{f}_x, \sqrt{\hat{f}_y^2 + \hat{f}_y^2}) \end{bmatrix}$$

Where arctan $2(y, x)$ is a four quadrant inverse tangent function .The solved pitch and roll estimated together with measured yaw ψ can be used to relate accelerometer measurement vectors to geographical-frame gravity vectors and realise corrdinate transformation . after the determination of initial pitch and roll for quasi-static moment , the attitude corrections could be performed on the basis of vectors from the following GPS fixes between two adjacent GPS sites of the bridge deck in a low dynamic mode .

Algoritm for GPS/accelerometer Integration



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BIOGRAPHICAL NOTES

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