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REVIEW OF UNDEWATER FLUID-STRUCTURE INTERACTION MEASURING TECHNIQUES

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Abstract. This research aims to provide a feasibility study for an underwater Fluid Structure Interaction (FSI) experimental methodology. The possibility of measuring a structural deflection under fluid load and the flow behaviour around the structure is particularly interesting with the rise of composite materials, due to their inherent flexibility that permits them to be designed to a range of loading conditions. A review study on the experimental methodology available is carried out so that, in the future, a FSI measurement system can be installed in an underwater environment such as a towing tank or a marine basin. A robust and repeatable experimental methodology will also provide researchers with a validation case for numerical FSI simulations. The feasibility study starts with a thorough investigation of the existing measuring systems with an assessment of what could be used in SSPA Sweden underwater facilities (i.e. towing tank and marine dynamics laboratory). Currently there is a lack of FSI experimental methods, especially for underwater environment. The large majority of the current studies does not account for the complexity of the FSI coupled problems, where the structural response affects the flow behaviour and vice-versa. Bringing different techniques together will allow simultaneous measurements to be taken in a dynamic underwater environment. This would be especially important for performance prediction and numerical codes validations of foiling structures to assess the effects of deflections and twist when phenomena like cavitation and ventilation occur.

1. NOMENCLATURE

a	Distance to load [m]
c	Chord length [m]
E	Young's modulus [Pa]
G	Modulus of rigidity [Pa]
h	Maximum camber [m]
J	Sectional moment of inertia [m^4]
K_I	Proportionality coefficient [-]
I	Second moment of area [m^4]
l	Span [m]
P	Applied load [N]
T	Torque [Nm]
t	Thickness [m]
γ	Shear strain []
δ	Displacement [m]
ε	Strain []
θ	Twist angle [radians]
σ	Uniaxial stess [Pa]
τ	Shear stress [Pa]

2. INTRODUCTION

Recent developments in composite materials have led to a wide variety of new application areas, ranging from the aircraft industry, renewable energy devices, high performance sports applications, to marine transport and components. The key enabler is the ability to custom tailor the composite materials to produce unique mechanical properties that optimise the performance of the structure being designed. Composite materials typically have very high specific stiffness and strength ratios with excellent resistance to corrosion, ultraviolet (UV) light and fatigue loads making these materials very attractive in marine applications [1, 2].

To fully utilize their anisotropic properties, composite structures may be designed with increasing strength in a particular direction, thereby tailoring the material properties of a laminate to achieve a desired deformation response. Due to the interactions between the bending-twist and extension-twist within the stiffness matrices of the composite laminates, it is possible to maximise the performance of a given structure, leading to the possibility of exploring design techniques that account for the internal flexibility of the composite laminates for a specific loading condition, introducing the concept of Passive Adaptive Composites (PAC).

A large number of studies have been performed on lightweight aero-elastic structures during the past twenty years, investigating the possibility of designing composite structures tailoring the properties for a desired purpose. However, the large majority of these studies still does not fully account for the complexity of the FSI coupled problem, where the structural response affects the flow behaviour and vice-versa, as most researches were based on numerical simulations with for example very accurate flow models and simplified structural response or alternatively highly detailed structural models with medium fidelity flow solvers. Without a two-way coupled FSI model, the modelling of the structural behaviour or of flow features cannot be realistic, e.g. an unsteady aerofoil deformation affects the aerodynamic efficiency and the noise associated with it [3].

Analytical solutions do not exist for most FSI problems [3, 4]. Likewise, it has proved challenging to acquire experimental measurements of dynamic coupling between applied fluid loading and a structure response. As a result, research in this area has mainly focused on coupled Computational Fluid Dynamics (CFD) and structural Finite Element Analysis (FEA) simulations. Even though numerical studies have been extensive, there is a lack of experimental validation cases for FSI problems and, for

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the limited cases that there are, the uncertainty in measurements is often unknown.

Moreover, even though some studies are now present in the aeronautics sector, the marine industry and therefore the underwater response to hydrodynamic loading is still an area that needs to be investigated. The harsh marine environment requires specific consideration of the durability, performance fatigue characteristic and potential failure mechanism of the material and structure when subject to long-term salt immersion, marine growth and reliability issues [1]. The low maturity of the experiments, low level of available technology and the lack of data and analysis tools for maritime applications are significant technological barriers.

In maritime applications, loading conditions can vary significantly due to interactions with the free surface, waves, currents, and adjacent bodies. In addition, cavitation and ventilation can develop for lifting bodies such as hydrofoils in water operating at high speeds and near the free surface. Added mass effects are posing additional challenges to take properly into account during the design process [5, 6]. Cavitation involves the formation and collapse of vapor bubbles caused by local pressure fluctuations [7]. Ventilation involves the entrainment of air into the flow around the body, and can occur simultaneously with cavitation [8, 9, 10]. The dynamic collapse of cavitation and/or ventilation bubbles can lead to large load fluctuations, vibrations, noise and instability issues [7]. The formation of small surface air bubbles can lead, with the use of composite materials, to resin peeling and fibre and matrix failure of laminated composites [11, 12]. A flexible hydrofoil, operating in water rather than in air will undergo an increased flow-induced deformation due to the higher fluid disturbing force.

In terms of experimental methodologies, especially looking at foil and vortex vibrations for both rigid and flexible hydrofoils, vibrations under hydrodynamic loading were investigated and simulated in [13]. Laminar to turbulent boundary layer transition induced vibrations were measured in [14, 15]. Recently, a strong coupling between the von Karman vortex-shedding and the structural response is measured in [16] with an interesting experimental setup for a morphing hydrofoil structure. However, all those presented methods don’t account for the complexity of FSI experimental methodologies in a dynamic underwater environment such as a towing tank or a marine basin. In the last year several research in France have brought forward the advances in hydrofoil measurements [17, 18] both investigating a hydrofoil behaviour in cavitation tunnel and in flume tunnel.

For light weight composite structures, where the modelling is more complex than for quasi-isotropic materials, to assess the validity of numerical FSI simulations we require the ability to measure the influence of fluid load on the structural response. As also shown in [6], added mass effects may be even more influential and difficult to predict for light weight composite materials than for traditional aluminium and steel structures. The possibility of using full-field non-contact measurement techniques such as Digital Image Correlation (DIC) and tomographic flow measurement (e.g. shake the box) allow the measurements to be taken on large investigated areas, without modifying the properties of either the structure or the flow.

With the increase of foiling boats in the high-performance sailing, leisure crafts and passenger ferries industries, the performances, failure modes and vibration characteristics of foils need to be accurately tested [19, 20].

This research project builds on previous work, where a fully coupled FSI methodology was developed in a wind tunnel to assess the response of a PAC aerofoil [20, 21, 22]. DIC and Particle Image Velocimetry (PIV), were used in-air to obtain high-speed full-field wing deformation and flow field velocity data in synchronous with forces and moments. The tests presented in [20, 21, 22] show that it is possible to tailor a structure to a desired specification, opening the possibility of designing adaptable structures for new applications encompassing aeronautics, mechanical and marine engineering.

The aim of the current research is to acquire the background knowledge necessary to provide the possibility of testing in an underwater controlled environment a number of hydrofoils. Those foils could be optimised not only for high performance sailing, but could also be fitted in fully electric vessels, to reduce both the CO_2 emissions and the resistance of the wetted surface area.

3. BACKGROUND ON MEASUREMENT TECHNIQUES

Digital Image Correlation (DIC), Particle Image Velocimetry (PIV) and Shake the Box (STB) are all full field, non-contact, light based optical techniques and have been used and developed for a variety of experiments separately since the 1980s [23, 24].

DIC is generally used to measure the strain or displacement of a structure subjected to load. It is a white light full-field noncontact measurement technique [25]. It involves the use of Charged-Coupled Device (CCD) digital cameras that register a series of images of a surface on which a randomised speckle pattern is applied. From these images, the displacement of the specimen can be calculated using a correlation algorithm to determine the motion of the speckle pattern within the field of view [26]. This technique has been used at different scales, from high magnification [27] to large scale structures [28]. Within the DIC software, the speckle pattern is mapped to calculate its deformation, allowing the displacements and strains of the underlying structure to be measured [26].

DIC analysis of a foil structure within the working section of a wind tunnel was developed at the University of Southampton [29]. In order to correctly measure the structural response of the flexible aerofoil, high-speed three-dimensional DIC (3D DIC) is used in a stereo configuration. The stereo angle between the two cameras controls the measurement accuracy of the out of plane deformation [25, 30]. This was very important in the wind tunnel study as the major mode of deformation was out-of-plane and the stereo angle was carefully considered with respect to the dimensional constraints of the tunnel [31, 32]. As demonstrated in [27], the variations in speckle pattern density and sizes influence the measurement accuracy. Therefore, it is possible to design a speckle pattern tailored for each experimental test. Moreover, to guarantee accurate measurements, the illumination intensity should remain stable during the experiments. A number of studies were performed on the accuracy of DIC measurement of specimens subject to high temperatures and extreme lighting conditions. In these cases, it is necessary to combine bandpass filters with monochromatic light. Those findings were brought together in the wind tunnel research to be able to accurately measure the deflections of a specimen with a fixed speckle size and density under varying lighting conditions. The DIC uncertainty was measured in-air during wind tunnel experiments [21].

DIC has been recently used in MARIN both in their cavitation tunnel to assess both uniform and non-uniform flows [33] and in the Depressurised Wave Basin [34]. Those techniques are focused on propeller deflection and use cameras looking through glass-like structures to assess the propeller deflection underwater.

Tomographic volume measurement with STB approach was initially developed in 2013 as a Lagrangian particle tracking [35]. The technique has been recently adapted to be used in underwater measurement with LED flashlights rather than with laser [36]. STB finds particles previously inserted in the water, with the same seeding technique as for underwater PIV, via 3D triangulation and "shakes" each particle in space to find the best possible match with the recorded camera images [37]. Then, for each detected particle, the particle images on all camera sensors are found and subtracted from the camera images. This yields residual camera images only showing the signal from the remaining particles, revealing previously obscured particle images. This Lagraingian approach is not possible with PIV which is an Eulerian method to measure the flow field.

Due to image aberrations and optical distortions, as for example shown in Figure 1, caused by the camera lenses and blurred particles, the same particle in different positions in the volume can generate differently shaped particle images on a camera sensor. This knowledge is stored in the Optical Transfer Function (OTF) optimized for the current recording [38].

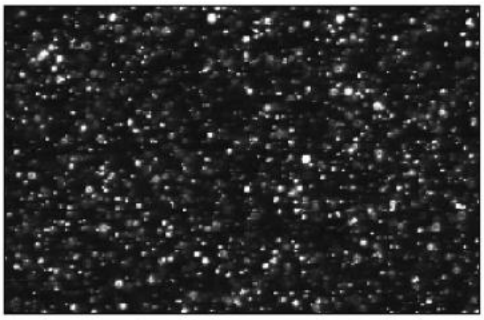

Figure 1: Unprocessed camera image of a TOMO-PIV experiment in air [38].

Having the cameras in the same position with respect to each other (Figure 2) aids with the recognition of distortions and spurious areas.

Figure 2: STB underwater arrangement from LaVision [39]. The 4 cameras are positioned in the bottom right corner of the torpedo-shaped housing. Their relative distance is always kept constant, aiding in particle tracking and calibration techniques.

The OTF serves as a basis for the STB processing. This ensures that even minor image aberrations are taken into account, which optimizes 3D particle position detection. The OTF also provides the appropriate particle images for computing residual camera images maximizing resolvable particle densities. In time-resolved STB a second order polynomial function is fit to each detected particle track. This yields a prediction of the particle position in the following step.

In the next time step, the algorithm prioritizes the search for particles in the vicinity of each predicted 3D particle position by 'shaking' the 3D particles into positions that maximize the match with the camera images. Then, the particle images are subtracted from the camera images. The resulting residual images contain only the particles that have yet to be tracked making the algorithm computationally efficient.

As shown by Jacobi for PIV arrangements, but applicable for most moving-underwater full-field measuring techniques, there are some critical areas to be considered [40, 41]. One essential problem, that in a laboratory environment, as well as in the wind-tunnel, could be addressed easily with changes in camera arrangements are stand-off distances. The distance to the specimen, that for

FSI cases include both the structural specimen and the flow around it, should be chosen in underwater measurements, not only for the ideal field of view size, but also to ensure non-intrusiveness and avoid flow disturbances from the torpedoes. When considering a towing tank environment, the seeding particles should also be investigated not only for the quality of seeds and dispersion level within the tank for flow measurements, but also to avoid disturbances to the structural DIC measurements. Within an air-environment in the wind tunnel (Figure 3) optical isolation between the structural and the flow measurements was ensured using magenta filters on LED lights [42]. As seen in Figure 4, the red bandwidth filters, ensure the highest transmittance level of light, approximately 90% further increased in the magenta colour, cutting-off the laser green-waveband that was captured by the PIV cameras.

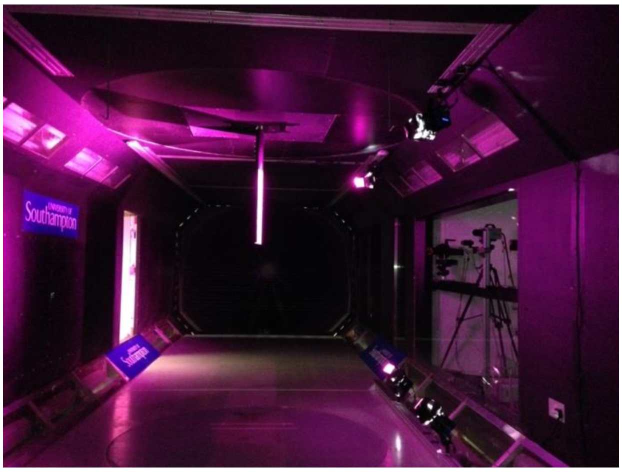

Figure 3: Wind tunnel setup as presented in [21, 42] to ensure optical isolation between the PIV and the DIC systems.

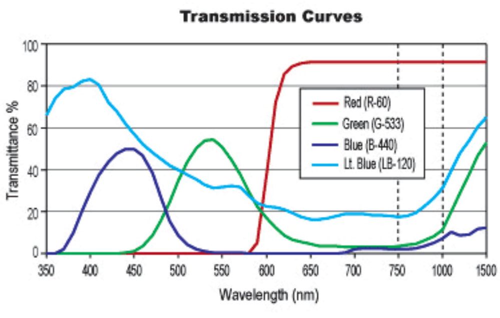

Figure 4: Transmittance curve for camera-filters [42].

When considering an underwater application where laser illumination cannot be used for safety purposes, the possibility of using white-light or blue high-power LED illumination needs to be considered. The selection of the different light source colour is linked to the choice of seeding particles. The application of fluorescent particles is known to prevent reflections from models and bubbles and the use of blue-flashlights with the corresponding camera filters will result in high-quality flow-measurements. If the FSI problem is investigated over a large area, with for example the structural deflection measured upstream and the flow wake measured downstream, a combination of white-light DIC set alongside the structure with blue-light STB positioned where the necessary flow measurements are taken can be considered as an option. The abovementioned set-up would be beneficial for flow measurements as it would avoid reflections from the specimen surface. While testing a hydrofoil, however, if events like cavitation or ventilation occur, light could be reflected not only near the free-surface but also by the air cavity bubbles formed on the specimen surface and shed downstream. The high light intensities from their reflections may result in exceedance of the saturation level on certain locations of the image sensor, especially for coupled charged device (CCD) cameras. Those problems are less affecting the newer complementary metal-oxide-semiconductor (CMOS) sensors [40]. The use of fluorescent seeding particles would reduce those reflection problems, at the expense of higher costs and difficulties in using them in large basins.

When testing high-speed hydrofoils, reaching the high-end limits of towing tank carriages to ensure Reynolds number and hence flow-features similarities, the main encountered issues are related to structural vibrations of both the carriage and the attached measuring devices. Most carriages are built on two rails that are carefully aligned with a laser and in case of long towing tank facilities are aligned accounting for the curvature of the earth. This ensures that the position of the towed model is not changed with respect to the free-surface. The carriages would move on metal wheels positioned on metal rails. The smallest imperfection in the rail-wheel system would therefore result in vibrations that are then transmitted to the carriage and specimen, with a change in frequency to the model itself and the underwater torpedoes. As both described systems are optical measurement techniques they rely on the perfect alignment of the cameras and, in case of vibrations, on their synchronous movement to avoid misalignments. Furthermore, the position of the cameras with respect to themselves and the specimens according to the initial calibrations will influence the overall accuracy. LaVision has worked on some of those issues, optimising the shape and the strength of the vertical strut attached to the torpedo to an Eppler E838 profile. Compared to the cylindrical shaped support tubes shown in Figure 2, lift, drag and overall deformation of the system are reduced to a minimum. Those results are however valid up to 7m/s, therefore further investigations on an optimised profile and structural integrity might be necessary for higher towing speeds, as the ones required to ensure Reynolds number similarity for hydrofoil testing.

Even for fully-coupled FSI experiment in an underwater environment in the near future, the recommended procedures detailed by the ITTC can be adapted to the new measuring systems to ensure that the criteria for testing procedures are followed and understood [44].

4. STRUCTURAL MEASUREMENTS

Hydrofoil systems used in high-performance sailing boats mostly rely on different types of manufacturing methods:

1. specialist one-off design and manufacturing of both the profile and lay-up used mainly by well-funded sailing teams for events such as the America's Cup or the Vendée Globe.
2. One-off or batch manufacturing for large development fleets such as the International Moth.
3. Batch manufacturing for one-design fleets such as the NACRA 17, IQfoil, Kiteboards etc.

Those different types of manufacturing methods will have dissimilar levels of accuracy, inversely proportional to their overall costs. The former type will have the highest accuracy and the finished foil would be as close to the design as possible with the building processes. The hydrofoils would be mainly manufactured with aeronautical-grade carbon fibres pre-preg and cured in autoclaves. Their internal lay-up would also be laid accurately to give the expected mechanical properties, tailored for the encountered sailing static and dynamic loads.

The second type of foils will range from pre-preg to resin infusion to hand lay-up, depending on the builder and on the sailor requests. This type of hydrofoils can be built with inputs from sailors and on-the-water testing, tailoring most of the types of foils to specific crew-weights and/or requests.

The latter type, being one-design will not allow the sailors to be involved in the design or manufacturing process. The building would range from pre-preg to resin infusion and the performance profiles (i.e. shape and thickness) and the mechanical properties will only be known to the approved manufacturers.

Composite materials indeed can have drastic changes to their mechanical properties with changes in the internal lay-up of the fibres. With fibres oriented at [0°, 90°, ±45°] composites specimens are considered quasi-isotropic with the same in-plane mechanical properties in all directions. However, the bending and torsional stiffness for the macroscopic structure will change when fibres are oriented at different angles, as the relationship of the stresses and strains must take into consideration the complete stiffness matrix as the stresses (σ and τ) and strains (ε and γ) are coupled to σ_1 and/or σ_2 in the two principal directions. This leads, under fluid loads, to a relationship between the forces and moments with the strains at laminate levels [18].

When analysing one-design foils, or indeed specimens where the material properties are unknown, it is possible to estimate the Young's modulus and the torsional stiffness of a structure, when subject to bending loads, following equations (1-3):

$$\delta_{max} = \frac{Pa^2}{6EI}(3l - a) \tag{1}$$

$$I = K_I ct(t^2 + h^2) \tag{2}$$

$$\theta = \frac{Tl}{JG} \tag{3}$$

An example of a hydrofoil structurally tested in a laboratory environment can be seen in Figure 5.

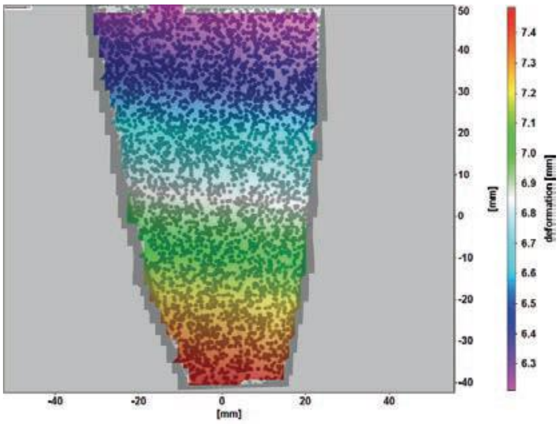

Figure 5: DIC deformation field for 178N load applied 14mm behind the leading edge of an International Moth horizontal foil [45].

Assessing the material properties and the shear centre location of hydrofoil systems, it is possible to investigate the expected deflections whilst sailing.

Having the possibility of testing a large number of specimens allows to understand the differences between them and the standard deviations in their manufacturing methods. Following those investigations, it is therefore possible to appreciate the differences in overall performances of a range of NACRA 17 hydrofoils, port and starboard, tested in bending load. The tests were replicating the boundary conditions of the daggerboard case, with fixed-fixed at the top case and fixed in displacement and free to rotate at the bottom hull-interface.

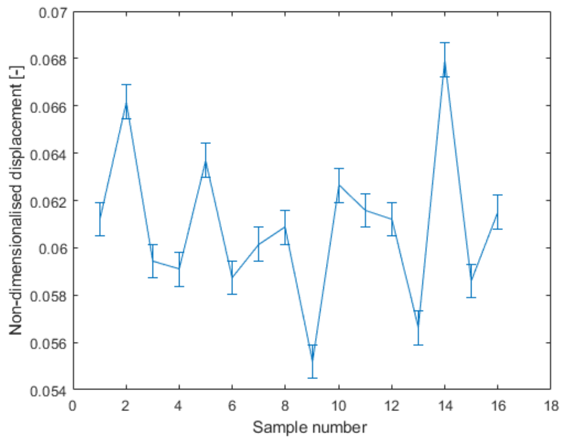

Figure 6: Non-dimensionalised displacement resulting from structural testing of a random sample size of one-design hydrofoils. Error bars represent the variation of the unloaded initial and final position of the specimens in the jig.

The load is statically applied at mid-span and at 25% of the chord with the displacements measured with a laser pointer. As seen in Figure 6 a random number of specimens has a large variation in bending response, changing the effective profile shape whilst sailing.

Being able to appreciate the complexity of fluid-structure interaction allows not only designers to tailor structures for specific loads, but also sailors to choose the best set-up for their specific sets of skills.

5. TESTING PLATFORM

In addition to the development of more accurate measurement techniques in laboratory settings such as the SSPA towing tank and Marine Dynamics Lab, testing and demonstrator platforms are important complementary tools when verifying new hydrofoiling technologies. With a test platform it is possible to test and verify full system concepts including control strategies and algorithms for un-stable hydrofoil configurations such as the KTH hydrofoil test rig for new electric motor-pods and roll stabilization techniques (Figure 7). Testing platforms are further very useful in verifying real scenario performance in waves, wind, with boat motions, etc.

Another important aspect is to minimise the risks of losing a hydrofoil during a real-event scenario (i.e. hitting an unidentified submerged object (USO) like a container or a marine wildlife that could result in abrupt breakage of the foil). Using a testing platform can help in developing foil casing and systems that are able to break in a controlled manner, without hindering the whole boat. This aspect of testing at model scale possible real-case scenarios could become attractive after the unfortunate race abandonment during the 2020 Vendée Globe edition. Many skippers in the two latest races were forced to retire or adapt to slower speeds after hitting USOs that damaged part or all of the foil structure and casing [46]. When considering the scalability of structural testing and the flow behaviour, it would be possible to develop such strategies as dynamic FSI experiments.

Figure 7: KTH test rig for new hydrofoiling concept with patented electric motor pods mounted on the wings and a unique roll stabilization configuration based on a mast rudder.

6. CONCLUSIONS

The paper presents a detailed review of the experimental methods able to describe fluid structure interaction events in an underwater dynamic environment. A feasibility study is carried out to understand the implications, limitations and advantages of being able to measure with full-field techniques in a towing tank. The necessity of experimental tests that are able to accurately replicate hydrofoils Reynolds number whilst measuring deflections and forces are becoming prominent to avoid full-scale or testing on a finished product, reducing the final cost and being able to assess the structural deformations at a design stage, taking advantage of those flexibilities. Moreover, the benefits of aligning underwater FSI tests, with structural measures and with testing platforms are explored for future assessment of hydrofoils within SSPA. Foiling boats are becoming more attractive to the general public, however issues such as reliability of the manufacturing methods and safety issues still need to be tackled. This feasibility study addresses some of those topics analysing them together with the advantages given by composite materials that allow designing for the expected loads, benefitting from hydroelasticity.

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