PROJECT FINAL REPORT

Grant Agreement number: 632539

Project acronym: VIAFUMA

Project title: Vibration analysis methodology for fuel manifold of lean burn engines

Funding Scheme: Collaborative Project

Period covered: from April 1st, 2014 to December 31st, 2016

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1 Executive Summary

The development of the lean burn engine is a significant step for the European aircraft engine industry to ensure a continuous reduction in fuel consumption and operational cost and stay competitive in an expanding global market. One of the fundamental design features of lean burn combustion is the use of staged combustion technology where a lean burning main zone and rich burning pilot are used to create lower pollutant emissions without compromise to system operability. Amongst other things this creates the need for a more complex fuel delivery pipework system to control the fuel distribution to the different combustion zones, leading to increased complexity, space constraint and an increased requirement for mechanical integrity to avoid reliability reduction. The lean burn programme under Clean Sky – Sage 6 has made significant contributions towards a flying demonstrator, but one major problem that must be addressed to make the lean burn system a reality is the correct prediction of the vibration behaviour of the fuel manifold system. A higher risk of rumble in the engine, and a larger amount of pipes for the staged fuel delivery increase the risk of HCF in such a system, and without a detailed analysis the failure risk of the engine may be too high.

The accurate prediction of the dynamic response of a fuel manifold assembly is a challenging task, since it consists of a wide range of components, including straight and bend pipes, different types of brackets that link to the casing, clips that hold the pipes in place, inserts to connect the pipes together, and sometimes damping devices to reduce the vibration response. Modelling each component in itself is already difficult, but once the system is assembled the prediction of the dynamic response becomes very challenging. The assembly of the components adds a large amount of joints to the system, introducing potential slip in the contact areas and a resulting nonlinear dynamic behaviour. During assembly misalignment can be introduced into the system which in turn can lead to pre-stresses in the pipes, which can affect the dynamic response. The presence of fuel will also impact the dynamic behaviour which will need to be considered in an analysis.

The general objective of VIAFUMA is the development of a fully validated modelling approach to predict the dynamic response of a lean burn fuel manifold system. Based on low and high order linear and nonlinear dynamic modelling the developed methodology will allow feasibility studies of the design during the early design development and enable detailed analysis during the later design stages. A bottom-up approach has been used to develop the modelling approach. Starting with the analysis and testing of the basic components of the fuel manifold system more and more complicated assemblies were gradually analysed and tested, to build confidence in the proposed modelling approach. Research in three main areas was conducted: (i) a low order modelling approach, based on shell and beam models and implicit nonlinear elements allowed fast feasibility studies of the system; (ii) a detailed nonlinear analysis approach using 3D finite element models was introduced for accurate prediction of the response amplitudes of sensitive components; (iii) an extensive test programme was carried out to provide validation data at low and operational vibration levels.

All the objectives of VIAFUMA could be delivered during the project, leading to a low order nonlinear modelling approach for the fuel manifold and high order models to investigate particular features in the dynamic response of the system. This report summarises all the technical achievements of VIAFUMA and presents the developed dynamic modelling strategy for pipe networks.

2 Project objectives

The general objective of VIAFUMA is the development of a new and fully validated approach to predict the dynamic response of a lean burn fuel manifold system. Exploiting basic and detailed linear and nonlinear dynamic modelling approaches will allow feasibility studies of the design during the early development and enable detailed analysis and optimisation during the later design stages. The immediate advantages lie in a general increase of life of the fuel manifold system, but the developed strategies will also help to reduce the weight of upcoming designs, leading to a lighter and more efficient jet engine.

VIAFUMA consisted of two Work Packages (WP), WP1 concerned with experimental work, and WP2 focussed on the analytic modelling approach.

2.1 WP1: Experimental

The overall objective of WP1 was to identify the linear and nonlinear dynamic behaviour of the basic, sub, and full assembly of the fuel manifold, and to provide reliable validation data for the newly developed analysis techniques from WP2.

Initially an experimental characterisation of basic pipe assembly (Task 3) was planned to:

- Develop specific test setup for each component of pipework assembly that isolates its vibration behaviour from the support structure. Straight and bend pipes will be investigated together with different types of mounts, inserts, and clips.
- Conduct low level impact hammer and shaker tests for each component, extracting operating deflection shapes with the help of a Scanning Laser Doppler Vibrometer (SLDV).
- Identify from frequency response the stiffness, damping and nonlinear behaviour of each component.
- Investigate the most basic assembly of a straight and bend pipe with the minimum amount of mounts, clips and inserts.
- Design, build and test a setup with a short length of pipe that can be pressurised with oil at different levels to characterise the mass loading and damping properties of the liquid inside the pipe.
- Introduce known misalignment in the assembly to achieve controlled pre-stressing of the pipework and evaluate the effect on the dynamic response.

This was followed by planned operational level testing of the fuel pipe assembly in Task 5:

- A sub-assembly will be tested consisting of several bend pipes, different mounting systems, inserts, and damping elements. Empty and pressurised pipework will be used
- A flat rigid and a flexible curved substructure will be used to determine the influence of impedance on the measured dynamic response
- The tests will be conducted with the High Amplitude Dynamic Excitation System (HADES) at Imperial College London. Operational level vibrations with sine sweep, random and wave form replication inputs will be used
- Non contact SLDV measurement techniques will be used in combination with strain gauges to determine the response of the system during testing

- The dynamic behaviour of the system will be measured, the main sources of nonlinearity identified, and the influence of pressurised pipework on the response investigated
- Misalignment will be introduced to the pipe assembly to generate a known pre-stress in the system, and its influence on the linear and nonlinear response investigated
- Several reassemblies of the setup will be tested to understand the variability in the measurement results and provide averaged values for the model validation

The experimental work was to be completed by operational level testing of the full casing assembly in Task 8, including:

- A simplified full casing assembly will be manufactured and tested on the HADES shaker system to reach realistic excitation levels in the required frequency range.
- The linear and nonlinear dynamic response will be monitored with a SLDV to obtain full field operating deflection shapes of the cylindrical structure.

2.2 WP2: Analytical

The overall objective of this task was the development of low and high order models for the prediction of the nonlinear dynamic response of a fuel manifold, including all its components.

This included an initial state of the art review on current pipe work modelling (Task 1) and then focused on the development of detailed models for the basic pipe-mount assembly (Task 4)

- Development of detailed three dimensional solid linear finite element models for each pipework component.
- Validation of the developed linear models against available test data from Task 3
- Nonlinear response predictions of the basic pipework assembly with the in house multiharmonic balance solver FOrced Response SuitE (FORSE)
- Inclusion of fuel effect in to the finite element model by distributed mass loading
- Analysis of pre-stress due to misalignment in the assembly and predictions of its effect on the linear and nonlinear dynamic response of the assembled system.
- Validation of the developed nonlinear models against available test data from Task 3

The knowledge obtained during the basic modelling was then to be used for the development of a high order modelling approach for fuel pipes on the casing (Task 6)

- A detailed solid finite element model of the rigid and flexible subassembly with and without pressurised fuel will be created and its linear dynamic response predicted.
- Based on the linear model of the subassembly a nonlinear dynamic analysis in FORSE will be conducted to predict the forced response of the pipework.
- The sub assembly models will be validated against the obtained test data from Task 5.
- A detailed full assembly model will be generated and its linear and nonlinear dynamic response predicted. This will involve large scale linear and nonlinear modelling with several 1000 nonlinear elements, for which new modelling techniques will be required.

- A comparison between the rigid and flexible support will be used to identify the influence of impedance of the substructure on the test results and to understand how obtained test data can be used to validate the full-assembly model.

As an additional approach to model the fuel manifold response a low order modelling approach for fuel manifolds would be developed (Task 7):

- A low fidelity model of each component, based on a mixture of shell and beam elements will be created to allow a fast computation of the dynamic results. These models will be validated against test and detailed FE data.
- Based on the identified main source of nonlinearity in the assembly, it is proposed to develop a new implicit nonlinear element for FORSE that allows a quick and reliable prediction of the pipework response. The element will require typical characteristics of the components as input, such as amplitude dependent damping and stiffness.
- The pre-stress in the low fidelity models will either be included by modifying the linear modelling approach, or adding a stiffness term during the nonlinear computation of the response.
- The assembled low fidelity model will be validated against the measured data obtained from Task 5 and 8.

Given the novelty of the set task, with a very limited understanding of the fuel manifold dynamic response, the objectives as stated in the Annex A of VIAFUMA, were adjusted to include the obtained knowledge and ensure the most effective way to analyse large scale fuel pipe networks.

3 Results of VIAFUMA

The VIAFUMA project was designed to provide detailed understanding of the fuel manifold vibration response and to introduce validated analysis tools to predict such behaviour. The starting point for the project was a basic understanding of the pipe work behaviour, and for this reason the project was designed with a strong experimental focus to provide the required understanding. Once a good understanding was obtained, appropriate modelling techniques were developed to replicate the behaviour and provide predictive tools for future designs.

The experimental work within VIAFUMA highlighted a strong nonlinear dynamic response of the pipe work and very large uncertainty in the response, due to the presence of a multitude of joints in the assembly. A large number of low and operational level tests were conducted on each individual basic component, subassemblies of the pipe work, and a full casing assemblies, in order to identify the crucial components in the dynamic response, their nonlinear interaction, and their behaviour on the global system. The pipe clips were identified as the main source of nonlinearity in the system, with all other components, such as pipes, brackets and connectors showing a linear behaviour. The interpretation of the resulting modal responses of the system proved to be very challenging so that new measurement technology was developed (high speed camera and digital image correlation techniques) to identify the dynamic behaviour of the system.

Throughout the experimental campaign a large variability in the test results was observed, which was attributed to the rather poorly defined contact conditions of the pipe-clip interface and large variability in the alignment of the clips with the rest of the assembly. The many testing campaigns of VIAFUMA let to the availability of a large data set, allowing an accurate identification of the linear and nonlinear parameters that define the dynamic response of a fuel manifold, and providing high quality validation data for the nonlinear modelling.

The developed modelling approach for the fuel manifold was mainly based on the experimental findings in the project, since at the outset of the project it was not clear what kind of behaviour had to be replicated, and how much detail was required to capture such behaviour. Initial testing revealed the need of nonlinear dynamic modelling, and highlighted large uncertainty in the experimental response data. This suggested a low order nonlinear modelling approach, which could cope more easily with the unknown sources of variability, instead of highly detailed nonlinear models which would struggle with the required input accuracy. The final modelling strategy for VIAFUMA was a combination of low order and high order modelling, where the low order models are used to predict the global nonlinear pipe work response, and detailed high order models were employed to investigate special features, such as the fuel effect or misalignments of the pipes.

A low order modelling approach was developed, based on a linear representation of the pipe work, the connectors and the brackets, and an implicit nonlinear dynamic model for the clips. Nonlinear identification techniques were used in combination with specially designed test setups to provide input data for the implicit nonlinear models. The models where than validated against operational level test data ensuring their predictive accuracy. The low order approach allowed fast and robust processing of the nonlinear dynamic response within the observed experimental uncertainty, satisfying the objective of an accurate prediction tool without the need of computationally expensive detailed nonlinear models.

Detailed linear and nonlinear finite element modelling was used when the low order modelling approach did not provide reliable accuracy, highlighting a minor effect of pressurised pipes and pipe misalignment on the dynamic response, and indicating the strong mass loading effect due to the fuel.

In the following an overview of the conducted work and the achievements of the project will be provided.

3.1 WP1 - Experimental

One main objective of WP1 was the identification of the dynamic behaviour of each component, and its influence on the basic assembly of the pipe work.

A basic pipe assembly was manufactured to represent the fuel manifold, containing most of the relevant components, including pipes, brackets (two different configurations) and clips (see Figure 1). This basic assembly was investigated very thoroughly, since it contained all the features of a real fuel manifold, and it replaced the real system for most of the project, since an industrial fuel manifold only became available towards the end of the program.

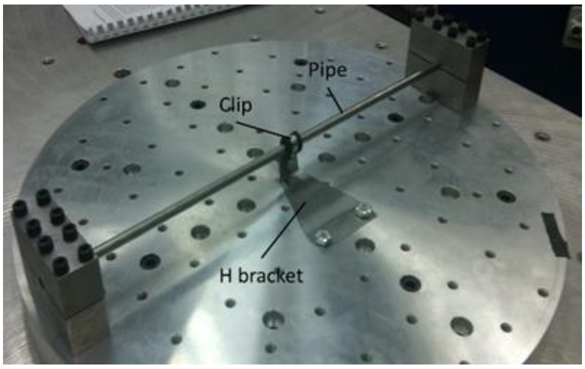


Figure 1 The developed basic pipe assembly

Each component was initially tested separately with an impact hammer, to identify its dynamic response which was used to update the FE models developed under WP2 (see Figure 2). A linear behaviour was found for this low level excitation with the impact hammer, allowing reliable updating and validation of the basic component models.

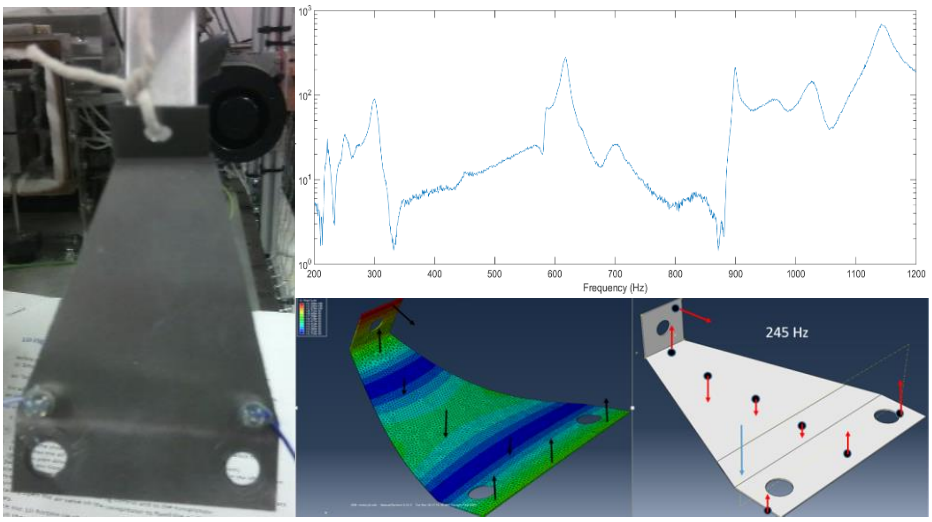


Figure 2 Component testing of the bracket and model updating.

Component testing in the High Amplitude Dynamic Excitation System (HADES) facility at much larger vibration levels identified a linear behaviour of the bracket with no major impact of geometric nonlinearities, but also highlighted a significant nonlinearity of the clamped pipe on its own. This could be related to the clamping mechanism of the pipe shown in Figure 3a) with its heavily nonlinear response (see Figure 3b). Since this strong nonlinearity from the clamp was interfering with the identification of the dynamic behaviour of the fuel manifold components, a new clamping configuration was developed for the HADES tests, leading to the pipe being held by the clips in Figure 3c). Large amplitude tests of the latter configuration led to significant nonlinear behaviour in Figure 3d) which was attributed to the frictional behaviour of the clips, making them a major focus of this investigation.

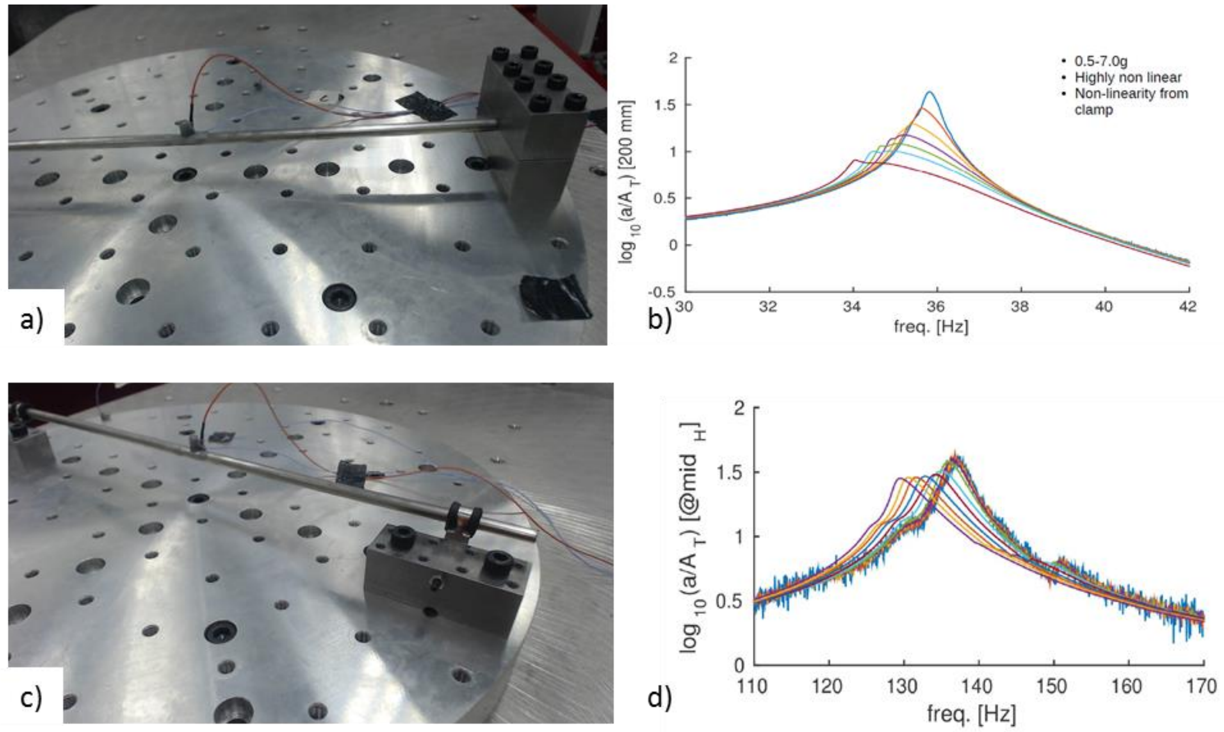


Figure 3 The a) original clamping mechanism with b) the resulting nonlinear response from the clamps, and c) the new clamping approach with d) the nonlinear behaviour due to the clips.

Based on these experimental findings, linear static tests were conducted on the brackets to provide validation data for the model of this component (see Figure 4a). The resulting stiffness values from the tests and the FE model in Figure 4b) show a linear relationship between force and deflection in Figure 4c).

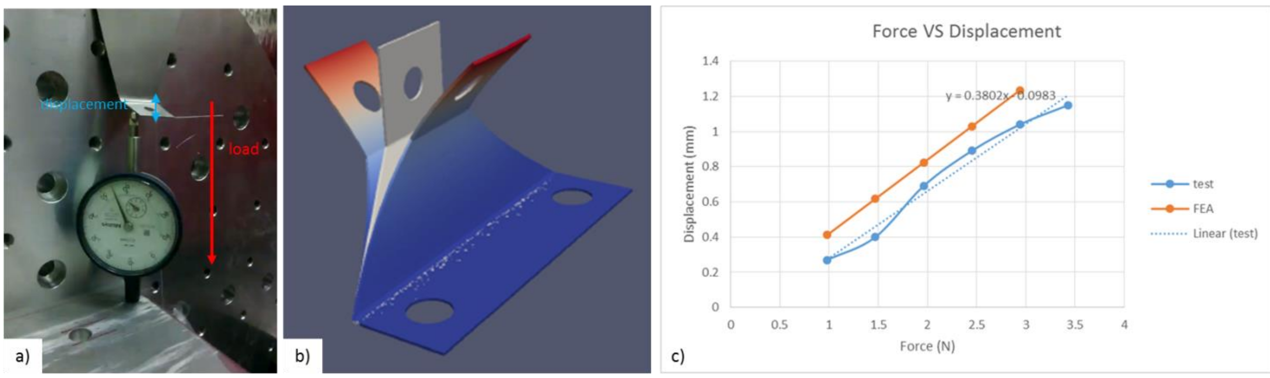
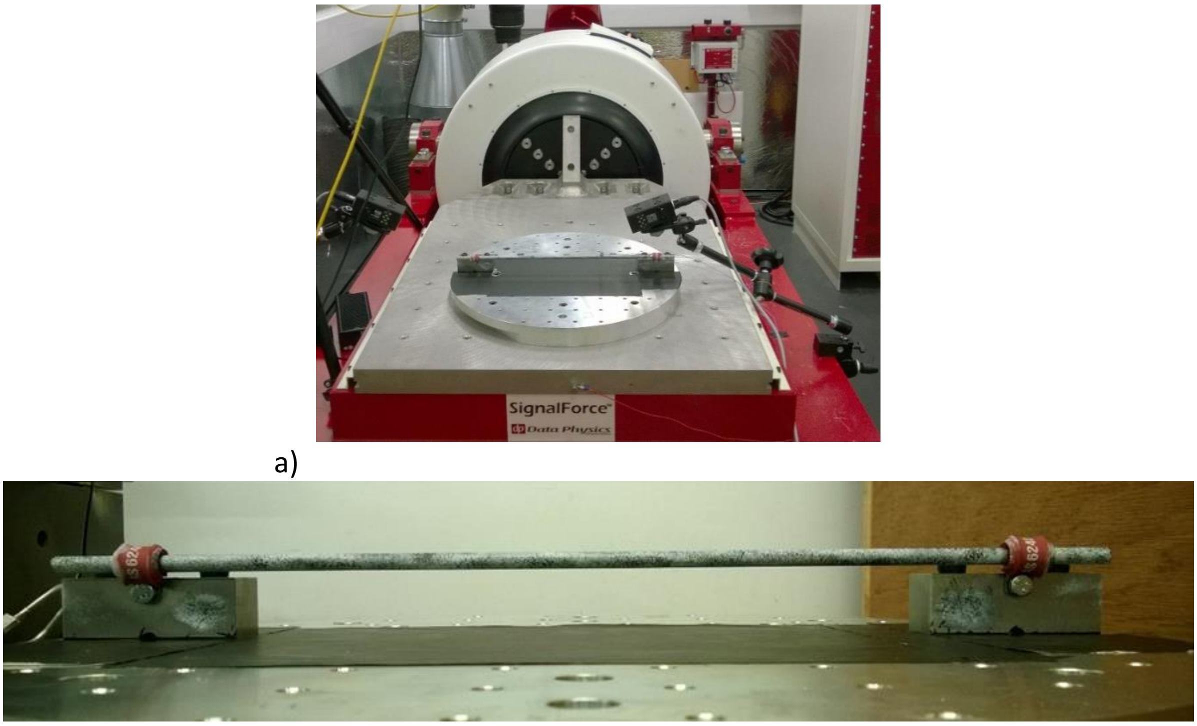


Figure 4 Static bracket testing, a) test setup, b) the FE model, and c) the extracted linear stiffness behaviour

A final set of tests of the pipe-clip-bracket assembly at large amplitudes led to highly nonlinear coupled response with the pipe describing complicated three dimensional orbital motions. This indicated a strong interaction between the different DOFs of the pipe, eliminating the possibility of a basic two dimensional analysis and making a three dimensional analysis necessary. As a result the modelling approach had to include at least 3DOF at each node, to capture the assembly motion correctly.

These initial results showed that the pipe and bracket behaved linearly, whereas the clip emerged as a major source of nonlinearity that introduced up to 10% frequency shift due to softening effects and increased damping at higher amplitudes. A strong coupling between the different DOF in the system has also been identified. Based on obtained experimental results the analysis requirements for WP2 could be defined as follows: Linear modelling of the pipes and brackets, and a nonlinear friction model for the clip.

In a next step a large amount of high amplitude testing was conducted to identify the nonlinear dynamic behaviour of the sub-assembly in Figure 5a), in order to provide understanding of its dynamic behaviour, identify the linear and nonlinear components, develop a standardised test setup for the parameter identification of the nonlinear elements, and provide validation data for the models.



a)

b)

Figure 5 Sub-assembly test setup a) HADES test setup and b) a close up of the straight pipe setup

The initial sub-assembly consisted of a straight pipe that was attached to two clips (see Figure 5b). The frequency response functions (FRFs) that were obtained during hammer testing, and high amplitude tests in HADES showed significant nonlinear responses characteristics with very strong coupling between the different response directions (see Figure 6). This behaviour could be attributed to the presence of the clips, further identifying them as the main nonlinear component of the assembly.

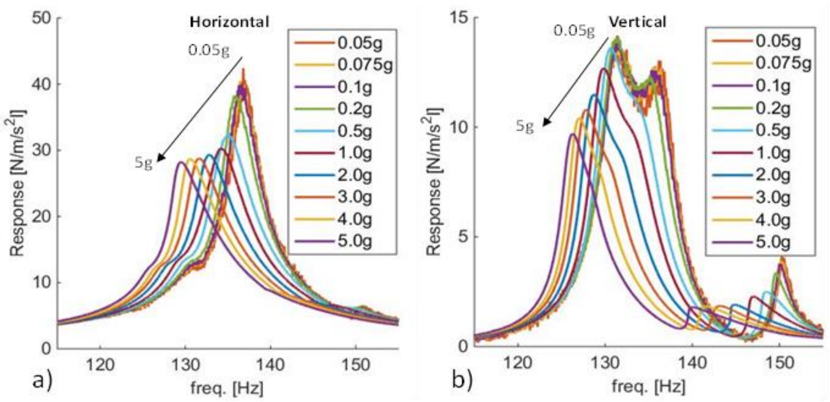


Figure 6 A typical nonlinear response of the sub-assembly in horizontal and vertical direction

To gain a better understanding of the response characteristic of the straight pipe, a separated test program focused on the Operating Deflection Shape of the system (see Figure 7), highlighting a strong variability in the response for certain modes, that prevent an accurate modal identification. The introduction of digital image correlation techniques in combination with a high speed camera system identified the presence of a traveling wave as the main source for the experianced variability. Since the traveling wave also prevented a reliable identification of the clip parameters for the nonlinear modelling, a modified test setup was introduced.

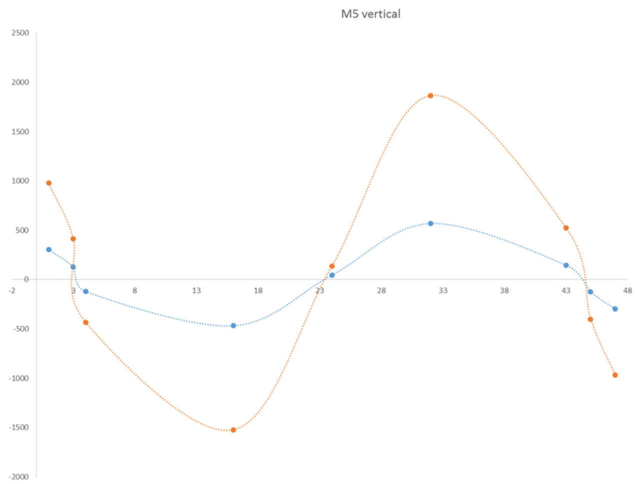


Figure 7 Operating Deflection Shape of 5th mode

The final pipe setup was based on a bent pipe with two clips, as shown in Figure 8a) to break the symmetry and avoid traveling waves. The resulting dynamic response in Figure 8b) was still highly nonlinear, allowing a clear identification of the clip input parameters, without the strong variability due to the presence of the traveling wave.

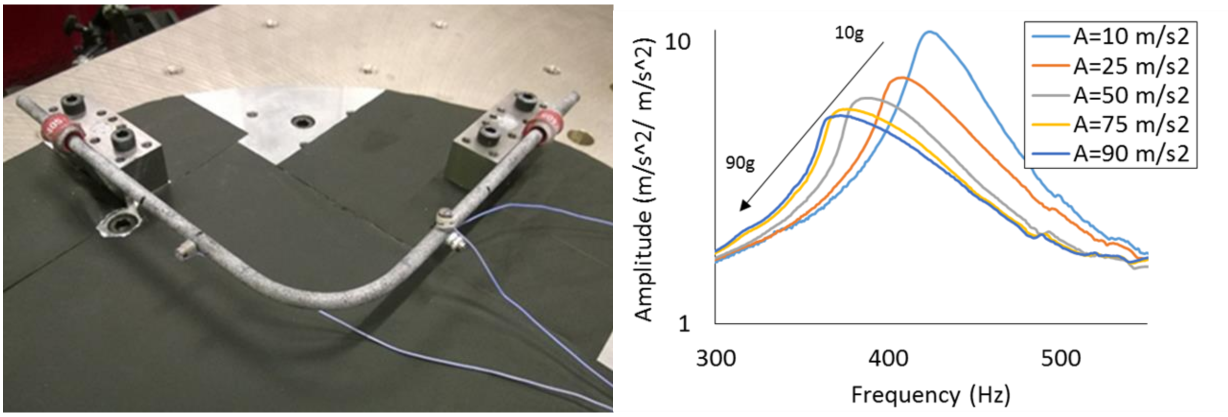


Figure 8 Final subassembly test setup with bent pipe and its dynamic response behaviour

During the development of the final test setup from Figure 8 additional variability in the response was observed, which could not be attributed to the previously discussed traveling wave. An extensive study was conducted to gain a better understanding of this variability in the response, looking at general reassembly repeatability, the influence of the experimental setup on the response, and specifically the alignment of the clips with regards to the pipe (see Figure 9). Resonance frequency variations up to 15% were observed due to these factors. Based on these finding a final test strategy for the identification of the clip model was proposed, based on a bend pipe, contact less measurement techniques (LDV), and a very well controlled and aligned test setup. To address variability of the clips themselves, averaging of several tests was recommended.

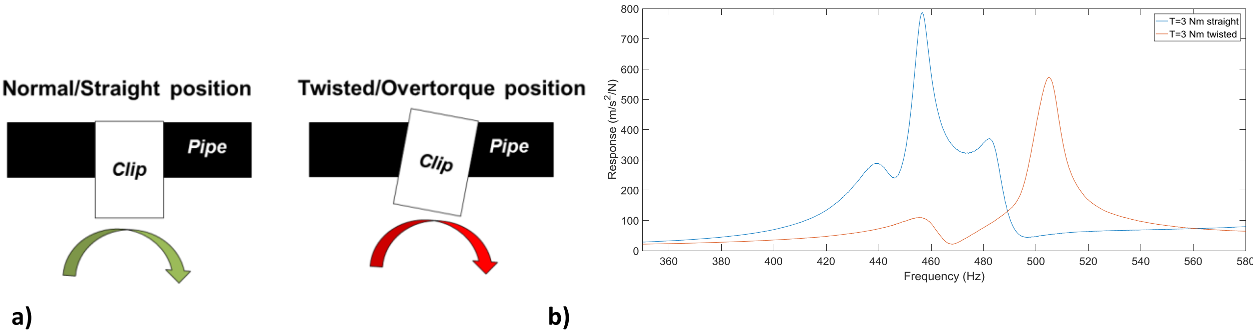


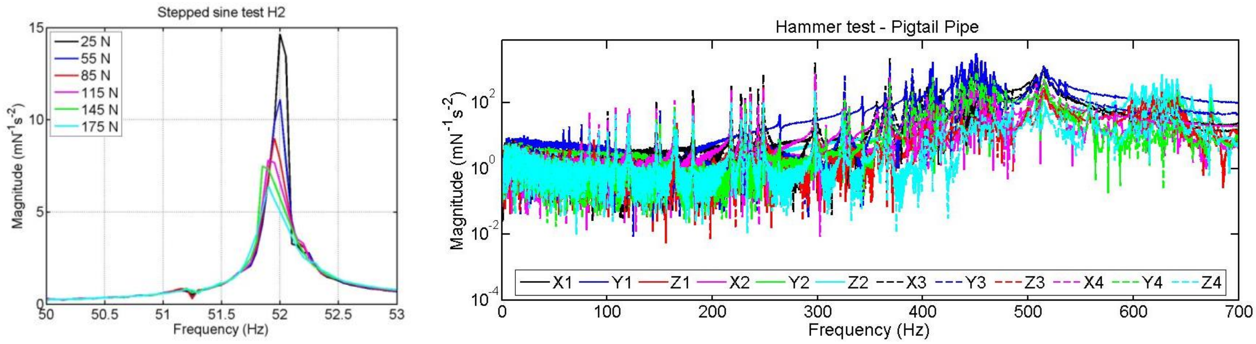
Figure 9 Uncertainty study a) different clip alignments and b) the effect on the response

The late arrival of the combustion engine casing from Figure 10a) led to a very intensive test schedule in the second halve of 2016 to generate the required measurement data for the full assembly. The dynamic system response was investigated with hammer and shaker test (see Figure 10b) up to operational levels of the casing. Initial tests on the casing allowed identifying the main mode shapes highlighting an extremely high modal density with a strong interaction of casing, fuel manifold and fuel supply pipes.

a) b)

Figure 10 The a) combustion casing with its fuel manifold system and b) the shaker setup for the cantilevered pipe excitation

The focus of the investigation was then shifted towards the fuel supply pipe in different configurations (free-free, cantilevered, full assembly) to obtain a better understanding of its dynamic response due to its complex shape, to investigate a potential nonlinearity from the connectors, and to provide validation data for the modelling. High level testing on the cantilevered pipe in Figure 10b), designed to strongly exercise the connector, showed the presence of some nonlinearity in Figure 11a) at very large excitation levels, but nearly linear behaviour in the operational range. When the pipe was attached at both ends, very linear responses were observed for the lower modes in Figure 11b). The nonlinear behaviour of some of the higher modes was attributed to the excitation of the clips in the manifold assembly which led to the conclusion that the connectors of the fuel manifold constitute a rigid linear link in the assembly and only their mass needs to be taken into account in a model.



a) b)

Figure 11 Frequency response data of the fuel supply pipe for a) the cantilevered configuration and b) the fully assembled system

The tests on the assembled structure identified the global dynamic response of the full assembly, but the high modal density (see Figure 11b) made it very difficult to distinguish between the operating deflection shapes (ODS) of the fuel supply pipe and other modes. To overcome this problem, a new measurement system based on High Speed Camera and Digital Image Correlation data processing was developed (see Figure 12a) which allowed capturing the ODS of the relatively complicated fuel supply pipe geometry. Special software was introduced to allow the tracking of the points on the pipe, and isolate its motion from the background vibration of the casing. The obtained results (see Figure 12b) and c) enabled the identification of accurate local pipe modes, and highlighted a strong interaction between the fuel supply pipe and the manifold for certain modes.

The latter led to the recommendation to include the supply pipe and casing dynamics for the assembly modelling.

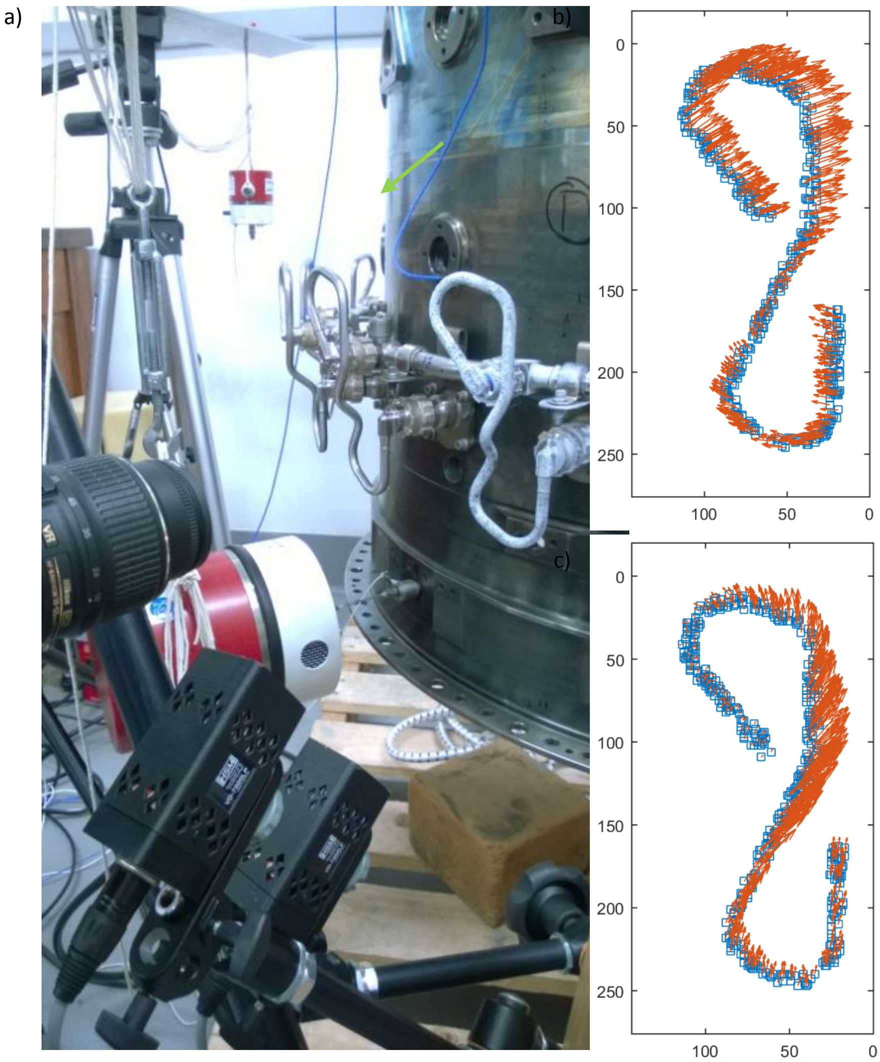


Figure 12 High speed camera DIC a) setup, b) local mode 1 and c) mode 2 of the fuel supply pipe

The data gathered throughout the experimental study of the fuel manifold system and its components was extensively used in the development of a modelling approach for such structures, to identify individual component model requirements, provide input data for the models, and allow validation of the models.

3.2 WP2 - Analytical

The current state of the art was investigated initially to gain a better understanding of the capabilities in pipe modelling. Several different approaches to model pipes were found, but a significant lack of available techniques for the analysis of assembled pipe network was identified, highlighting the need for fundamental research in the area.

As an initial step in the modelling procedure, detailed three dimensional finite element models of the different components were generated, and their linear dynamic behaviour was validated against experimental data.

A linear analysis with the pipe in its clamp configuration (see Figure 3a) led to significant differences between the measured data and the predicted results, highlighting the need of nonlinear models. In a next step a detailed nonlinear dynamic analysis with friction joints was attempted to capture the influence of the clamps on the response. For this purpose, a novel nonlinear meshing approach for cylindrical structures was developed (see Figure 13), to allow the use of the available nonlinear solver FORSE (in-house multi harmonic balance solver). The developed approach was based on the use of Salome-Mecca as a pre-processor to generate the required mesh information, Nastran to solve the linear model and provide the reduced models to the nonlinear solver FORSE. An overlying code structure was supplied that linked the different programs together and dealt with the conversion of the data for use in the nonlinear dynamic analysis. Most of this process was fully automated, allowing the quick generation of different nonlinear contact meshes.

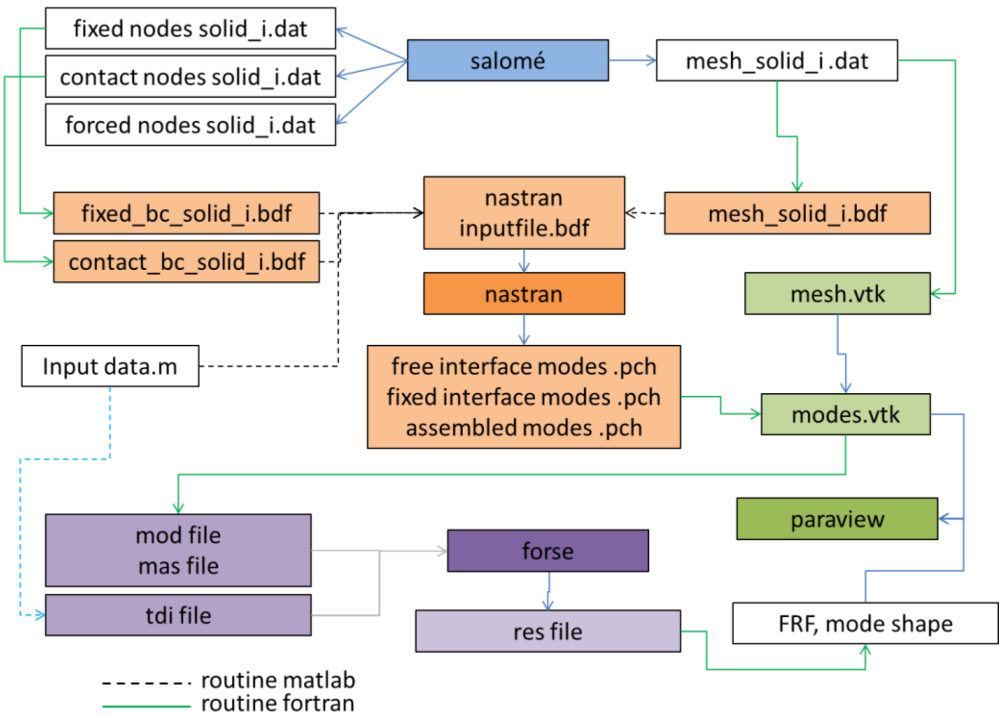


Figure 13 Introduced meshing approach for cylindrical structures

An analysis of the clamped pipe model was conducted to investigate the effects of the nonlinear behaviour, and in particular the impact of the geometric nonlinearities. For this purpose, an existing research code had to be modified to enable the computation of the response. Extremely high and unrealistic excitation levels were required to activate the geometric nonlinearities of the clamped pipes in Figure 14. Based on these results the nonlinear behaviour in the measured FRFs was attributed to friction only, allowing the use of linear models for the pipe work, since the activation levels of the geometric nonlinearity were deemed unrealistic for operational use.

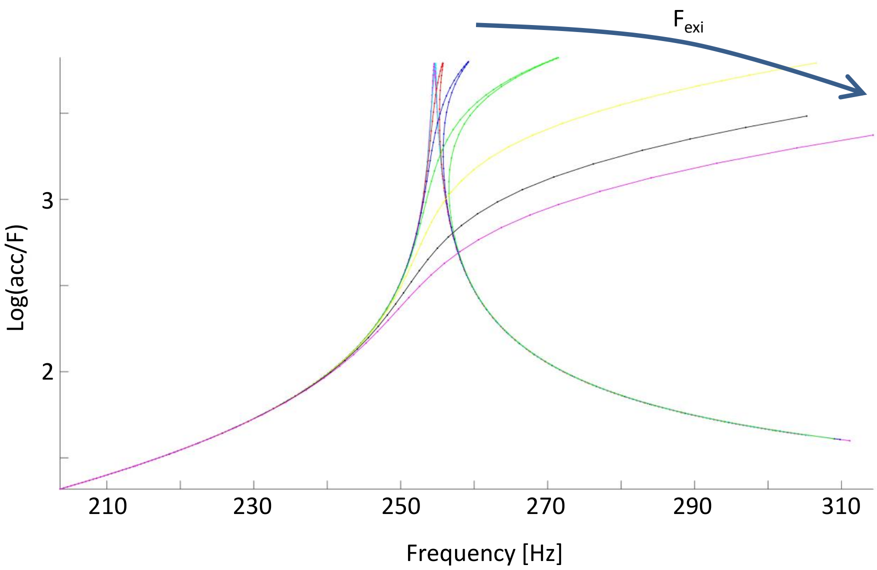


Figure 14 FRF for geometric nonlinearities of the pipe

To minimise the nonlinear effect of the clamps, experienced during testing, they were replaced experimentally by a bracket configuration (see Figure 3b), leading to some significant softening and an increase in damping at higher amplitudes. An explicit FE model of the pipe and clip was generated (see Figure 15), with particular care on the modelling of the rubber inset of the clip, to investigate its influence on the dynamic response.

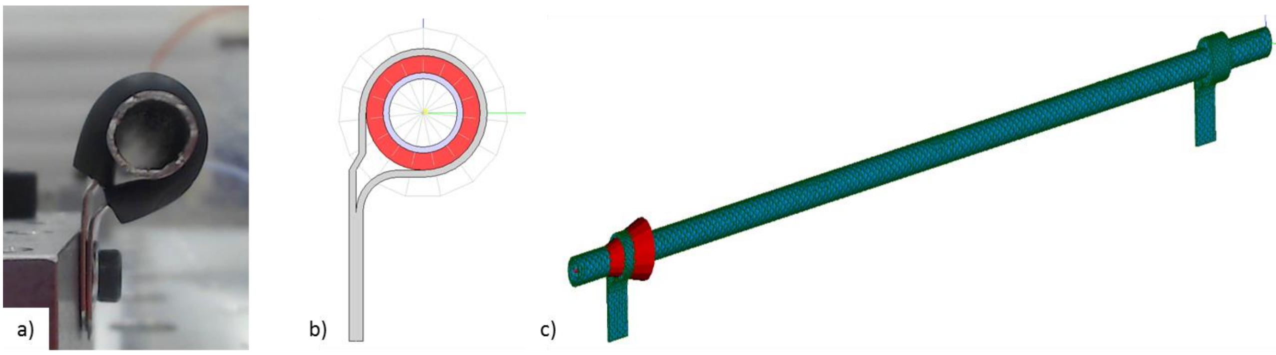


Figure 15 A close up of the rubber clip, b) the detailed FE representation of the clip, and c) the pipe clip assembly model

The resulting FRFs in Figure 16 for a linear analysis with an excitation in the horizontal direction show good agreement between the measured (Expe pipe H) and predicted response (CA pipe H), with the main resonance frequency captured quite accurately. The experimentally detected coupling between the in and out of plane motion (see strong response of 'Exp pipe V' for a horizontal excitation) can also be replicated with the FE model (CA-pipe V), indicating its capability to capture this particular feature.

At this stage it was discovered experimentally, that the repeatability in the pipe-clip assembly was very poor, preventing any reliable nonlinear dynamic analysis due to the unknown contact conditions at the frictional interfaces between the clip and the rubber inset and the inset and the pipe. The target of the detailed high order modelling approach was therefore slightly modified to provide understanding of particular features of interest, whereas the global nonlinear dynamic response analysis was conducted with the help of a low order model, which was much more robust against assembly uncertainties. Detailed FE models for straight and curve pipes were created. These models where used to understand the effect pressurised fuels in the pipe and pipe misalignment on the dynamic response of the system.

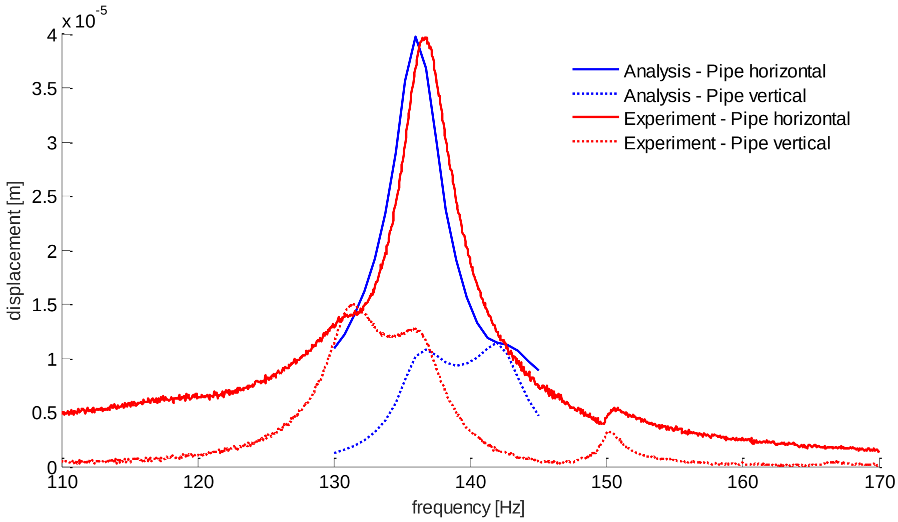


Figure 16 Results of the coupled pipe-clip vibration analysis, FE and experimental comparison

When considering the effect of fuel inside a pipe on the dynamic response, two aspects are of importance, the stiffening effect due to the pressurisation of the liquid and the added mass effect. To investigate the impact of pressure on the dynamic response of the pipe, a re-computation of the dynamic stiffness matrix, based on a static stress analysis, was used to combine static internal pressure with a dynamic analysis (see Figure 17). It could be shown that very large pressures (>80bar) were required for the chosen pipe geometry to lead to any significant stiffening effects. Curved pipe geometries were thereby more sensitive to stiffening effects and the mode shape also played an important role when computing the dynamic response of pressurised pipes. A significant mass loading effect due to the fuel inside the pipe was observed. Three potential modelling approaches were investigated, ranging from a basic increase in density of the pipe material to the 3D modelling of the fuel body inside the pipe. No significant differences in the resulting dynamic behaviour could be observed, so that the simplest approach, based on increased density was recommended for future use. At high pipe pressures the stiffening effect began to counteract the mass loading effect of the fluid, leading to frequencies that were similar to the empty straight pipe.

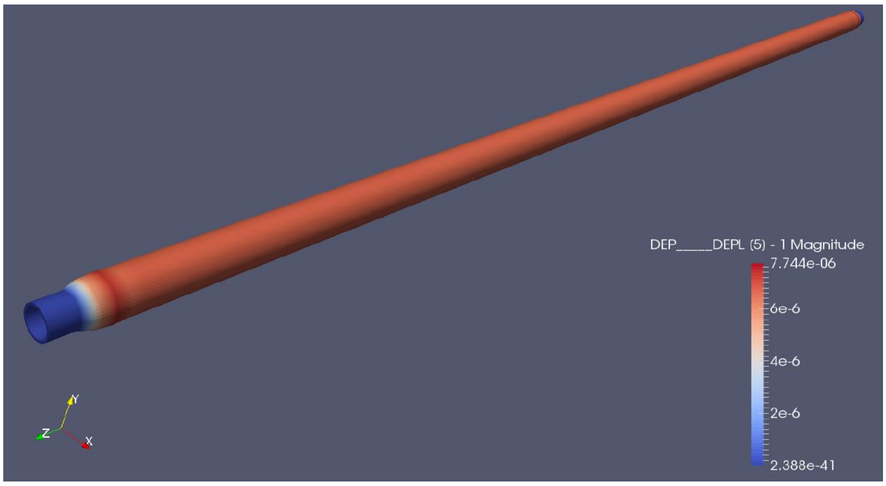


Figure 17 Pressurised straight pipe

A further concern for the prediction of the dynamic response of a fuel manifold was the effect of assembly misalignment in the pipes. To investigate the significance of this effect, detailed FE models were used, which were statically deformed in axial or transverse direction to simulate assembly misalignment and introduce a known level of pre-stress. An approach was than developed to project the resulting new stiffness matrixes onto the dynamic analysis, to introduce the nonlinear effect to the prediction of the resonance frequencies and mode shapes.

For a straight pipe it was shown, that an axial misalignment had by far the largest effect on the resonance frequencies (see Figure 18), where an axial elongation of 0.2% let to a frequency increase of 60%. The natural frequencies of the lower modes were stronger effected by the pre-stress but the change in the mode shapes was negligible. Since the forces for such an axial elongation where significantly higher than was feasible for a manual assembly, it was concluded that the axial stiffening effect could be neglected for the dynamic analysis of the fuel manifold.

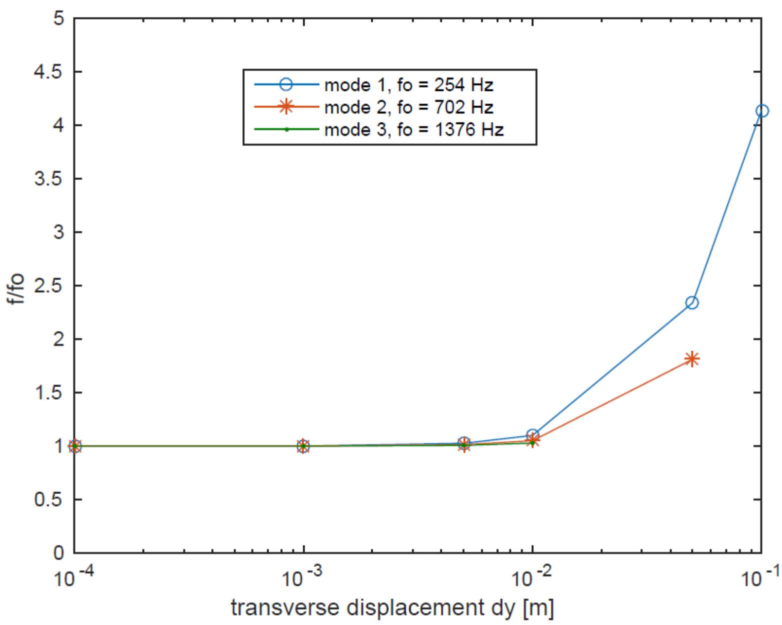


Figure 18 The effect of axial misalignment on the resonance frequency of a straight pipe

Very high transverse displacements were required to introduce any significant stiffening effect, making this type of displacement an even more unlikely source of nonlinearity in the fuel manifold system. This results was validated with experimental data (see Figure 19) where no stiffening effects due to misalignment could be observed. Further investigations on curved and circular pips did not show strongly different behaviour, also some slightly larger changes to the mode shapes appeared for very high misalignment levels. Based on all these detailed results it could be concluded that for all practical purposes of fuel manifold modelling the effects of assembly misalignment could be neglected.

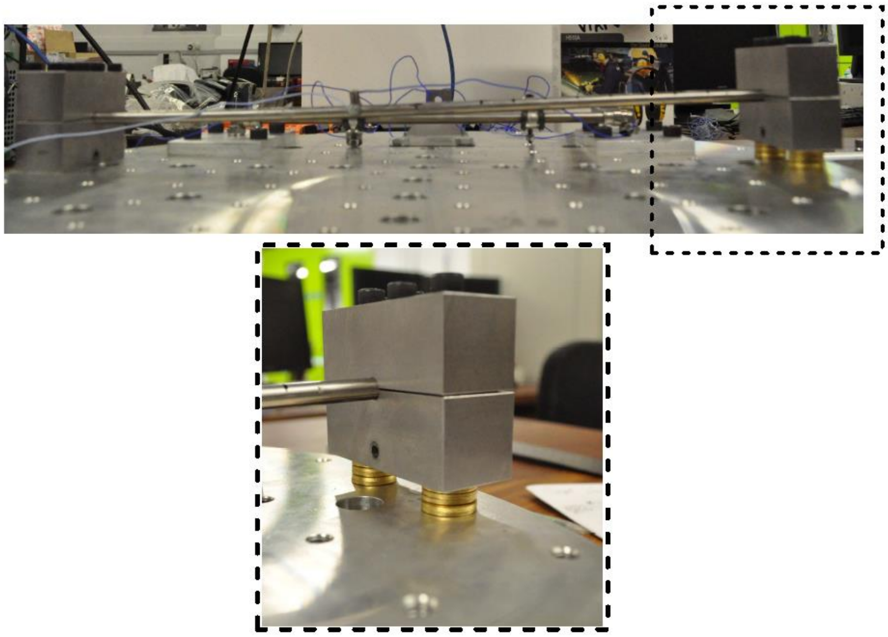
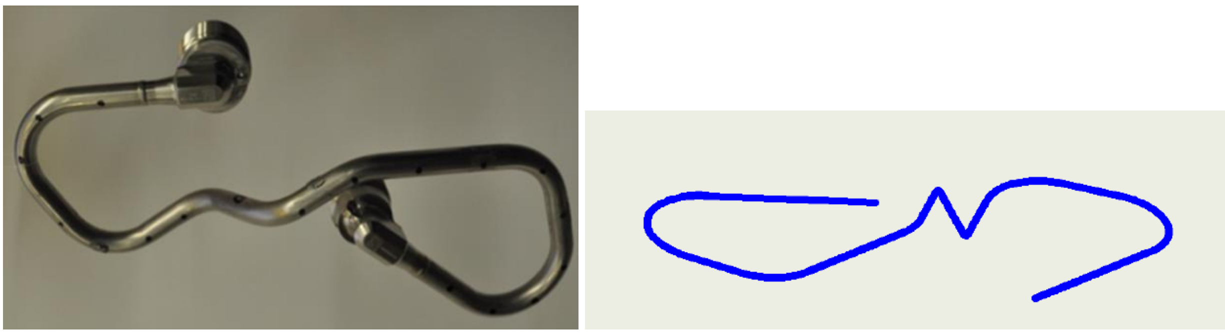


Figure 19 Experimental misalignment study

The pipes on a fuel manifold assembly can have very complex geometries, to accommodate for assembly restrictions and thermal expansion during operation. Accurately capturing the motion of these complicated geometries with a low order nonlinear modelling approach is challenging, and it was recommended to use detailed finite element analysis for components such as the fuel supply pipe in Figure 20 to gain a better understanding of its dynamic behaviour.



a) b)

Figure 20 Fuel supply pipe, a) real structure and b) finite element model

The detailed fuel supply pipe model allowed an accurate identification of the motion of such a pipe (see Figure 21). A comparison to the detailed ODS data obtained from digital image correlation data (see Figure 12 b) and c), indicated an strong effect of the connector mass and the stiffness of the supporting structure on the dynamic response.

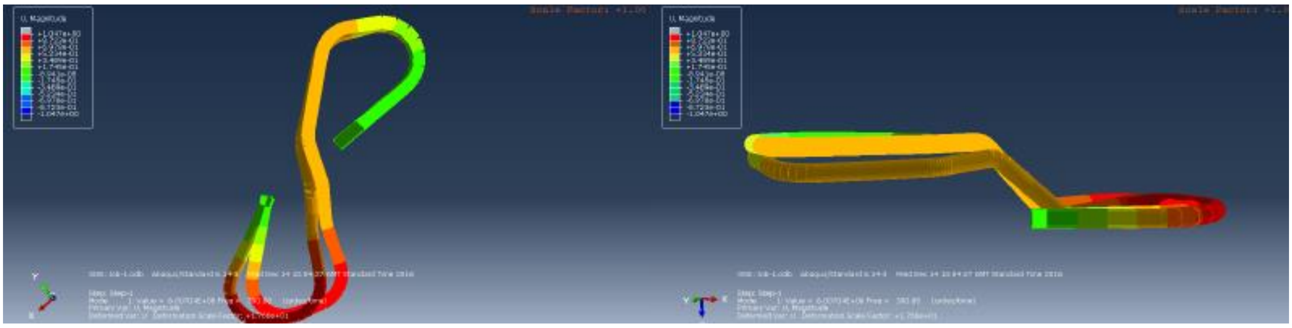


Figure 21 Fuel supply pipe, a) real structure and b) finite element model

For the global response predictions of the fully assembled fuel manifold, a low order modelling approach was developed. It was strongly based on the experimental findings and the explicit finite element results allowing a fast and accurate computation of the nonlinear dynamic response of the assembly.

The different pipes were modelled with Euler-Bernoulli beam elements since their simplicity and their low computational cost made them an interesting option for the low order model. Due to the high length to diameter ratio of the pipe and the presence of a thin pipe in the fuel manifold, these simple elements provided good accuracy. The bracket element was based on the creation of an initial detailed FE model, allowing to consider all kinds of bracket shapes (See Figure 22) at an early design stage. Craig-Bampton reduction was then used to reduce the size of the model for faster computation.

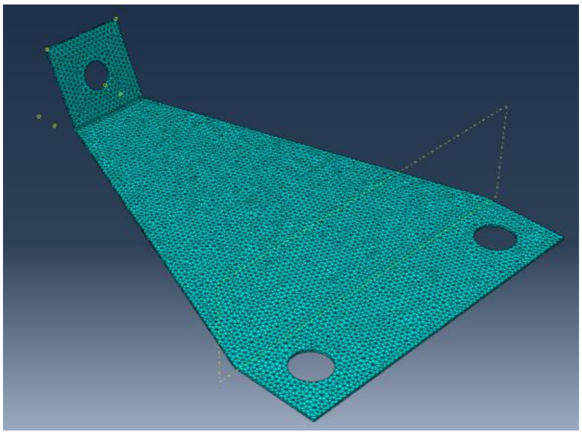


Figure 22 Bracket FE model

A comparison with experimental data highlighted the accuracy of the chosen approach for the linear elements of the fuel manifold, leaving the nonlinear clip element as the main challenge. A simplistic, yet accurate representation of the clip was required to capture the nonlinear dynamic response of the fuel manifold correctly. Based on measured data, and a detailed linear finite element model (see Figure 23) the main linear and nonlinear degrees of freedom for the clip were identified.

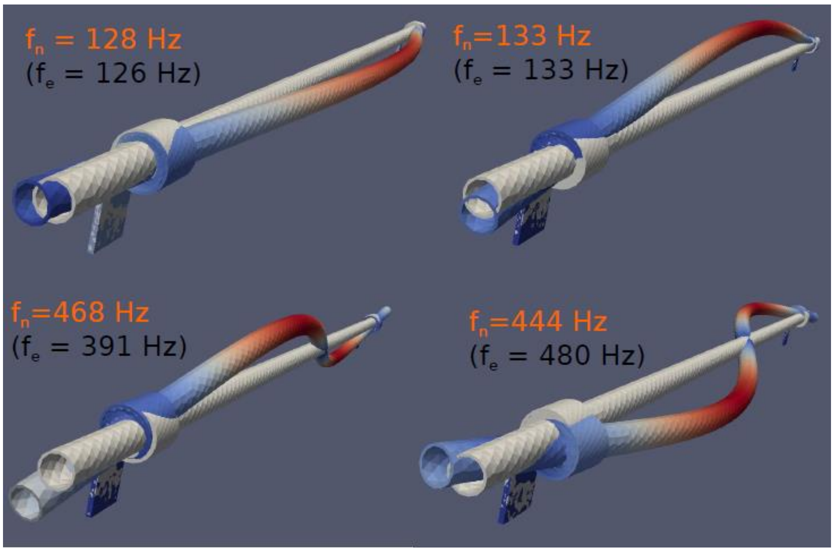


Figure 23 Detailed finite element model of the pipe and clip

Based on the previous investigation, a nonlinear representation of the clip was introduced which was able to capture all the significant motions. A set of linear or nonlinear translational and torsional springs (5 DOF) were used in combination with a simple mass element to represent the structural behaviour of the clip, and a nonlinear damping element was added to represent the detected viscoelastic and frictional behaviour between the pipe and the clip (see Figure 24).

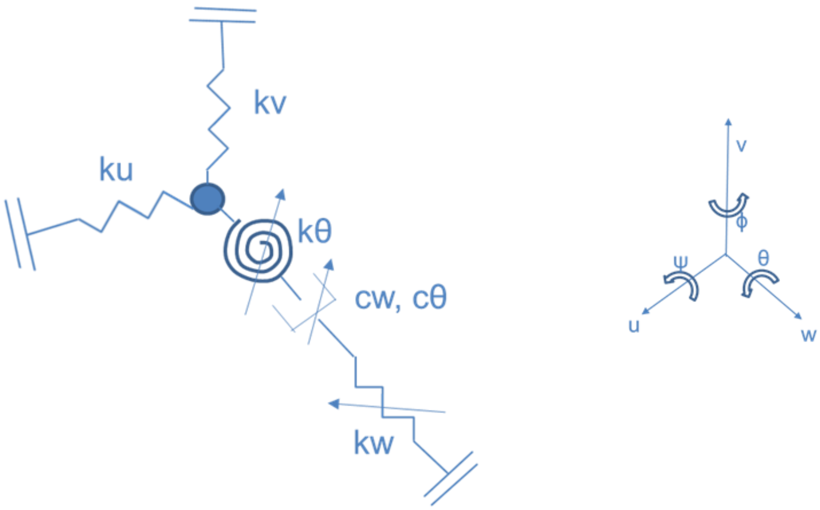


Figure 24 Low order nonlinear clip model

One particular challenge with the chosen modelling approach were the input parameters for the clip model. Nonlinear model identification was chosen for this purpose, since the very large uncertainties in the clips made a detailed modelling approach implausible. The experimental setup in Figure 8 was used in conjunction with a low order model of the pipe with two clips to identify the correct linear and nonlinear parameters.

For the parameter identification a genetic optimisation algorithm was used in combination with the multi-harmonic balance solver FORSE to find the clip input parameters, by minimising the difference between the measured and predicted frequency response functions. An new framework for this nonlinear parameter extraction was developed (see Figure 25), to integrate experimental data analysis and nonlinear dynamic response predictions within the parameter optimisation.

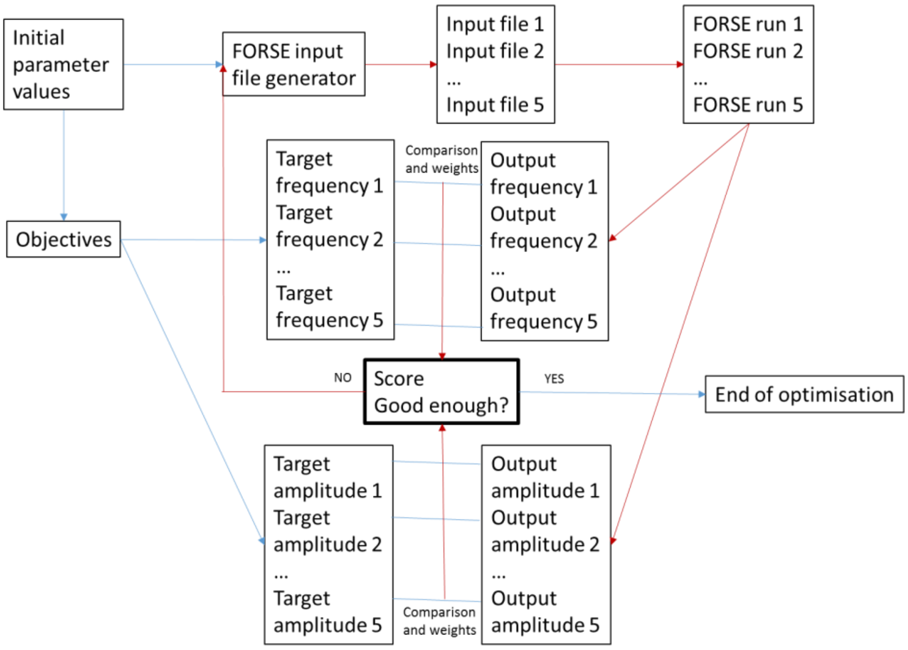


Figure 25 Parameter identification framework

The resulting low order nonlinear dynamic models for the clips were than used to predict the response of a pipe system, and the response prediction was compared to experimental data. It could be shown that the predicted response was within the measured scatter of the experimental results, confirming the reliability of the introduced approach.

3.3 Conclusions

The main objectives of VIAFUMA were to obtain a detailed understanding of the dynamic behaviour of complicated pipe assemblies, and develop an appropriate modelling approach to model the observed behaviour.

A large range of low and operational level tests was conducted, on individual components, sub-assemblies, and on a full assembly, leading to the identification of a strongly nonlinear response driven by the clip element, and a relatively linear behaviour of all the other components. Extremely high modal density was observed on the assembled structure, leading to the development of a high speed camera and digital image correlation technique to track the vibration of individual components. Large observed response variations after reassembly, could be attributed to the alignment and orientation of the clips after a detailed study of the experimental setup. Based on these findings a test setup was developed that allowed a reliable extraction of the input parameters for the modelling approach, and provided good quality validation data for the system.

The experimental understanding of the dynamic behaviour of a pipe network, led to the development of modelling approach to predict its dynamic response. A combination of detailed finite element analysis and low order nonlinear dynamic modelling was employed to reach this objective. Detailed models where thereby used to investigate particular effects of interest and determine their impact on the dynamic response, while a novel low order modelling approach was used to capture the global dynamic response. It could be shown that fuel pressure and misalignment in the pipes only play a minor role, but features such as the geometry of the pipes, the mass loading effect, and the nonlinear components in the assembly must be included in the modelling approach to achieve accurate results. Based on the findings a low order modelling method was developed and validated, which is able to capture the dynamic response within the uncertainty of the experimental data, and which provides a much better understanding of the fuel manifold vibration response.

4 Impact and Dissemination

The need for the work in VIAFUMA emerged from the Clean Sky project SAGE 6 for the development of a lean burn fuel system. Lean burn combustor systems are a key technology to reduce NOx emissions of future aircraft engine generations. They use high overall pressure ratios and turbine entry temperatures to substantially reduced pollutant emissions compared to current technology and support the future long term technology goals of the ICAO Committee on Aviation Environmental Protection (CAEP) as well as the future visions laid out in ACARE 2020 and Flightpath 2050.

One particular challenge for lean burn systems is the large number of pipes required, which can significantly increase the likelihood of high cycle fatigue failure due to vibration during operation. VIAFUMA was designed to provide the required inside into the nonlinear vibration behaviour of the pipes and supply predictive capability to model the dynamic response of fuel manifolds accurately in advance.

VIAFUMA has led to a significant increase in understanding of the pipe work vibration for industry, already having helped with the analysis of an existing systems, and providing predictive tools for the design of the upcoming lean burn systems. The outcome of the project has helped to shape design practice and provided confidence in the design approach. It has already been used by industry to analysis the vibration behaviour of a Trent 1000 aero engine fuel manifold, providing invaluable information on the vibration behaviour of the fuel supply pipes. For future engine generations, and in particular for the lean burn engines, the outcome of VIAFUMA will allow the optimisation of the fuel manifold system during the development program of the engine thereby reducing weight, minimising the need for engine test data, reducing wear in the components, extending the fatigue life, and lowering the risk of failure of the system. This will support the introduction of lean burn systems and lead to lower cost during the development process of the engine, by eliminating potentially expensive re-designs.

The better understanding of the vibration response of fuel manifolds, provided by VIAFUMA, will ensure an increased reliability and operational safety of the structure. The avoidance of vibration induced fatigue and failure will allow longer maintenance intervals on the engines, leading to lower operational costs for the airlines, and less risk of an engine shut down, reducing the risk of an engine failure and thereby increasing passenger safety. Design optimisation of the fuel manifold system with regards to vibration response will support the introduction of lean burn systems, and also lead to reduced weight, with only the minimum number of clips and brackets present in the setup. This will lead to more efficient engines, which on one hand will further reduce the operational cost for the airlines due to a reduced fuel consumption, and on the other hand lead to a reduction in CO_2 and NO_x emissions over the lifetime of the engine.

The VIAFUMA team has published on reviewed journal publication and attended six conferences and workshops to disseminate information to the scientific community. In addition, reports, regular link calls and face to face meetings were used to share the outcome of the project with the industrial costumer, to inform their design process as the program progressed.

5 Contact details

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